Chapter 5
Specification of the Vulnerability of Physical Systems

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Abstract The general methodology presented in Chap. 2 of this book, has been conceived in order to be general enough to be adequate for each system. The purpose of this chapter is to decline this methodology to the specificity of each physical system considered: i.e., Buildings, Water Supply System, Waste Water Network, Electrical Power Network, Oil and Gas Network, Transportation Network, Health Care System and Harbours. Each system is described based on its structure and taxonomy, on the dependencies it shares with the other systems, on the available methods to describe its systemic vulnerability and, finally, on the existing indicators to evaluate its performance, but also its functionality according to the societal needs.

5.1 Introduction

The scope of the SYNER-G project includes the definition of some of the systems that comprise the *Infrastructure*, namely the inhabited areas (common buildings), the utility networks (water, waste-water, power, and gas supply networks), the transportation networks (roadways) and some critical facilities/systems (harbours and health-care system). While Chap. 2 of this book has exposed the general methodological framework that allows the representation of all these systems in

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an object-oriented architecture, the objective of the present Chapter is to describe each system through various angles. First of all, the object-oriented architecture of the whole Infrastructure is further developed for each considered system, in order to specify the system down to its lowest-level component. Then, the **specific** *attributes* of each class or sub-class are defined: these properties are complementary to the ones already defined in Chap. 2 for **abstract** classes, and they are required to accurately describe each particular system. Interactions between systems are also investigated for each system, based on their type and the modelling assumptions used. Then, various possible approaches to "solve" each system (based on the complexity level of the analysis) are reviewed: the ones that have been implemented in the SYNER-G project are further detailed in terms of *methods*, in the sense of the UML (Unified Modeling Language) terminology (i.e. basic functions or routines used in the solving algorithm). Finally, relevant performance indicators at component- and system-level, whose applicability depends on the level of analysis chosen, are defined.

This specification work is necessary in order to characterize most of the particular features and behaviours of each system, while still staying within the methodological framework defined in Chap. 2. The computation of carefully selected performance indicators serves the purpose of assessing indirect losses (i.e. uninhabitable areas, utility or accessibility losses) that, if combined with direct losses from physical damages, can yield a first partial estimate of the overall socio-economic impact of an earthquake. This key point is enhanced here by the need to feed the socio-economic models defined in Chap. 4 (e.g. emergency shelter needs, health-care capacity), thanks to the various outputs from the specified systems.

5.2 General Specifications

Each system is described according to three main characteristics: (i) the lists of its elements, which is given through the taxonomy of the systems, (ii) the support it provides for the society, which is provided through the system evaluation and the selection of appropriate performance indicators and (iii) the treatment of interactions with the other interconnected systems.

5.2.1 Taxonomy of Systems and Their Components

Following the framework of the general SYNER-G methodology, each class of systems is composed of sub-classes that are used to describe the various types of components, based on the geographical extent and their function within the system:

- **Cell classes** are used to define inhabited areas (i.e., Buildings System) and contain information on buildings' typologies, population or soil land use policy.

- All **network-like systems** (i.e., Water Supply, Electric Power, Gas Network and Road Network) contain two types of sub-classes (Edges and Nodes), which are further sub-divided in specific classes, according to the role played by the component within the system: network nodes can be stations, pumps, reservoirs, sources, distribution nodes, etc.
- **Critical facilities** such as components of the Health-Care System are modelled as point-like objects.

Each of the sub-classes is specified with its characteristic attributes and UML-methods, depending on the type of system considered. For instance, initial properties of the objects may include geographic location, area, length, soil type, typology, associated fragility, capacity, connectivity with other components (for networks), etc. Once the simulation is running, the specific UML-methods update the object properties, such as damage states, losses within each cell or remaining connectivity.

5.2.2 System Evaluation and Performance Indicators

Four main types of system evaluations are considered in the SYNER-G approach:

- **Vulnerability analysis:** This level of analysis (also called Level 0) considers only the potential physical damages of the components of the systems, with no consideration of functionality of either the elements or the whole system.
- **Connectivity analysis:** This level of analysis (Level I) analyzes the probability of the demand nodes to be connected to functioning supply nodes through undamaged paths. In this approach the damaged components are removed from the network and the adjacency matrix is updated accordingly, thus pointing out the nodes or areas that are disconnected from the rest of the system. This qualitative approach is used for all utility networks (water, electricity, gas) and the road transportation system.
- **Capacity analysis**: This level of analysis (Level II) considers the ability of the system to provide to the users the required functionality. This type of approaches is quantitative. For utility networks, graph algorithms and flow equations can be used to estimate capacitive flows from sources (e.g. generators, reservoirs) to sinks (i.e., distribution nodes), based on the damages sustained by the network components (from total destruction to slight damages reducing the capacity).
- **Fault-tree analysis**: This level of analysis concerns critical infrastructures, where multiple conditions are necessary for the systems to ensure its task. This type of approach aims to evaluate the remaining operating capacity of objects such as health-care facilities. The system is broken down into structural, non-structural or human components, each one of them being connected with logic operators.

Performance indicators, at the component or the system level, depend on the type of analysis that is performed. Connectivity analysis gives access to indices such as the connectivity loss (measure of the reduction of the number of possible paths from sources to sinks). Capacitive modelling yields more elaborate performance indicators at the distribution nodes (e.g. head ratio for water system, voltage ratio for electric buses) or for the whole system (e.g. system serviceability index comparing the customer demand satisfaction before and after the seismic event). The fault tree analysis method is generally used for the derivation of fragility curves for specific components that comprise a set of sub-components (e.g. health care facilities, water treatment plants).

5.2.3 Treatment of Interdependencies

The systems are impacted by the other systems by a set of different dependencies. These dependencies can work in one way, i.e. the state of one system conditions the functioning of another system, or two ways, where two systems are mutually dependent, or interdependent. Rinaldi et al. (2001) defined four types of interdependencies: "cyber, logical, geographic and physical".

Out of these four interdependencies, three types of interactions between systems are considered for the present SYNER-G specification:

- **"Demand" interactions**: they correspond to a supply demand from a given component to another system. For instance, the presence of densely populated cells in the vicinity of a given distribution node (e.g. from a water supply or electric power system) will generate a substantial demand on the supply system. Another example could be the number of casualties that will put a strain on the treatment capacity of health-care facilities.
- **Physical interactions**: they are associated with exchanges of services or supplies between systems, like the supply of potable water to inhabited cells, the supply of transportation capacities by roads or the supply of power to various network facilities (e.g. water pumps) by electric generators.
- **Geographical interactions**: they are involved when two components are located in the same area and when the damage of one of them is directly influencing the physical integrity of the second one. For instance, the collapse of buildings in city centres can induce the blockage of adjacent roads due the debris accumulation.

The interactions between systems that are treated in the frame of SYNER-G are listed in Table 5.1: ***D*** stands for Demand, ***P*** for Physical and ***G*** for Geographical interactions.

It should be noted that the "demand" interactions are considered as static, since they are estimated only once, in order to avoid the presence of any feedback loops that would introduce dynamic systems, which are left out of the SYNER-G scope. As a result, this table of interdependencies governs the order in which each system has to be computed during the simulation runs, in order to maintain a straightforward analysis scheme.

Table 5.1 Main interdependencies between systems that have been implemented in SYNER-G

		BDG	EPN	WSS	GAS	OIL	RDN	HBR	HCS
Buildings	**BDG**	/	**D**	**D**	**D**		**D/G**		**D**
Power	**EPN**	**P**	/	**P**	**P**	**P**		**P**	**P**
Water	**WSS**	**P**		/					
Gas	**GAS**	**P**			/				
Oil	**OIL**					/			
Roads	**RDN**	**P**					/	**P**	**P**
Harbour	**HBR**						**D**	/	
Hospitals	**HCS**						**D**		/

5.3 Specification of Each System

This section is devoted to the description of each considered system, in terms of internal structure, interactions with other systems, solving algorithms and performance indicators.

5.3.1 Inhabited Systems

Inhabited buildings are somehow different when compared with the other networks and critical infrastructures considered in SYNER-G. Indeed, they do not experience direct intra-dependencies (i.e. each part of the system can function independently of the other states of the systems) and are mainly dependent of the other systems. However, they are still considered as a system, because each component contributes to the general capacity of the system: to shelter people.

5.3.1.1 Structure of the System and Input Attributes

Buildings are the basic point-like component of building aggregates/agglomerates/ blocks (where buildings may or may not be in contact, with the ensuing interactions), which are delimited by roads. The description of the vulnerability of an urbanised area at a large scale (e.g. a census tract, where several such building agglomerates are present) implies fragility analyses for each building typology and the use of statistical data on the incidence of each typology in the building population.

There are different levels to consider the inhabited zones. The region encompasses the whole study area, which is then divided in cells, and in sub-cells, according to the localisation of buildings, and their characteristics (see Fig. 5.1 and Table 5.2). This sub-division allows the refinement of the computation of impacts of the earthquake in the area where the density of assets and population is higher.

The various attributes from the Cell are then aggregated at the Region level, in order to generate indicators at the urban or regional level.

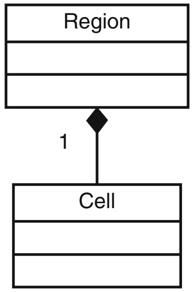

Fig. 5.1 UML class-diagram of the buildings system (BDG)

Table 5.2 Attributes/properties of the cell class

Group	Attribute	Description
Geometry	vertices	Points on a diagonal of the cell
	centroid	Average of vertices, where seismic intensity is predicted
	adjacentCells	Pointers to grid cells sharing a border with the current cell
Physical Damageability	buildingTypologies	$n_T \times 1$ vector with percentages of buildings in each of the n_T typologies (BC)
	fragilitySets	$n_T \times n_{DS} \times 3$ matrix with n_T fragility curves for each of the n_{DS} damage states, specified in terms of IM, median and logarithmic standard deviation
Socio-economic	population	(EAU)
	households	(EAU)
	income	(EAU)
	unemployment	(EAU)
	bldgUsage	4×1 vector of percentages of usage of cell area in use types Green, Residential, Commercial, Industrial (LUP)
Interdependence modeling	refNodes	Pointers to reference nodes in each of the other systems (WSS, EPN, RDN, GAS, OIL, etc.)
State variables recording cell state	states	$n_E \times 1$ collection of properties that describe the current state for each of the n_E events (fields: buildingDamage, utilityLoss, with subfields for each utility, buildingUsability, displacedPopulation, casualties, supplyRequirements, etc.)

BC, EAU, LUP: projected from Building Census, European Urban Audit, Land Use Plan, or other relevant data bases

5.3.1.2 Interdependencies

Interactions of the built areas with other systems are manifold; the main ones are defined in the following list:

- **EPN ➔ BDG [Physical]:**
  Damage to the EPN can reduce the service level in the struck area, possibly below tolerance thresholds, thus leading to population displacement and demand on the Shelter model described in chapter 4.

- **WSS ➔ BDG [Physical]:**
  Damage to the WSS can lower the service level in the struck area, possibly below tolerance thresholds, thus leading to population displacement and demand on the Shelter model.
- **GAS ➔ BDG [Physical]:**
  Damage to the GAS system can reduce the service level in the struck area, possibly below tolerance thresholds, especially in adverse weather conditions, thus leading to population displacement and demand on the Shelter model. Also, leakage of the gas system can induce fires, which could damage buildings.
- **RDN ➔ BDG [Physical]:**
  Damage to the transportation network can block access to damaged buildings hindering emergency response.
- **BDG ➔ WSS [Demand]:**
  Fires in buildings can be triggered by earthquake induced damage thus raising the water-supply demand on the WSS (when this is not independent of the FFS).
- **BDG ➔ RDN [Geographical]:**
  In an urban setting, structural damage to buildings produces debris that can cause road blockages.
- **BDG ➔ HCS [Demand]:**
  Structural and non-structural damage to buildings may result in casualties that need to be treated in a health-care facility and hence determine the demand on this system.

5.3.1.3 Methods for Systemic Analysis

In practice, while the vulnerability assessment of a single building of special interest is based on a detailed and specific structural analysis, the global evaluation of vulnerability (i.e., for several hundreds or thousands of buildings at urban or regional scale) relies mostly on the use of statistical or probabilistic vulnerability functions. These functions represent the "typical" behaviour of a group of buildings characterized by a limited number of similar physical parameters.

Whatever the procedure used, a vulnerability assessment study of common buildings at urban or regional scale is based on the following elements:

- A building typology and its census within the studied area: while the seismic behaviour of buildings cannot be specified one by one, it is required to define a building typology based on structural criteria (i.e. material used, height, bracing system), that can be more or less accurate.
- A damage probability matrix or fragility curves that correspond to the chosen typology: for a given building typology, they represent the percentage of buildings that exceed a given damage state, for a given level of seismic intensity. Extensive details on fragility functions for different building typologies are provided in the Chaps. 3 and 4 of Pitilakis et al. (2014).

The very large number of buildings at regional or even at an urban scale can then be treated according to two possible approaches:

- The first one considers each building individually. Goda and Hong (2008) developed a methodological framework to estimate the influence of the degree of spatial correlations and simultaneous occurrence of the seismic solicitations on the assessment of seismic risk for buildings. Four classes of correlation are considered, namely, no correlation, full correlation, and partial correlation with/without intra-event components. Estimations of damage are performed on sets of buildings subject to a series of earthquakes for a given period of time, according to the four classes of correlation. The authors conclude that a bad estimation (either over-estimation or under-estimation) of the real correlation has big influence on the distributions of damages to buildings but do not influence the average value of this damage.
- The second approach is carried out when a detailed individual analysis of all buildings is not feasible. In this case, buildings are modelled in 'statistical terms' as populations for which information is given at the level of the buildings group (group size depending on the refinement of the analysis and varying from a single block to a larger extent of the urban territory). Information includes percentage of each building typology within the group, with associated fragility models, population, income, education, and other urban and social features.

Due to the diversity of scales and existing inventories, both approaches have been used in the SYNER-G project. The study of Vienna has been conducted with both individual and statistical approaches (Chap. 8), while the buildings of Thessaloniki have been analysed with the second, i.e. statistical approach (Chap. 7).

But due to the fact that most of the areas of concern will be more similar to Thessaloniki than Vienna, regarding the size and the existence of detailed inventories, the second approach has been adopted in the SYNER-G methodology (Cavalieri et al. 2012), where improvement of spatial resolution is adopted for areas with high population density, in order to reduce the variability of buildings' typology existing in each cell. The influence of spatial refinement (i.e. higher resolution grid) on the variability of the mean damage ratio for large groups of buildings has been shown by Bal et al. (2010).

Then, the analysis of the built-up areas within the SYNER-G framework is achieved through a set of UML-methods (Table 5.3).

5.3.1.4 Performance Indicators

Performance indicators of the built area system are expressed at the region- and cell-level, depending on the requirements of the systemic analysis. In particular in SYNER-G the performance indicators have been selected to require the need of the socio-economic analyses (Chap. 4). The corresponding performance indicators are the following

Table 5.3 Most relevant UML-methods of the Region class

Method	Description
evaluateBuildingDamage	Evaluates the damage state for each typology of buildings in the cell employing the corresponding set of fragility curves and the current intensity at the centroid
retrieveUtilityLoss	Reads from the reference node of each utility system the corresponding service level and computes a total (weighted sum) utility loss
evaluateBuildingUsability	Determines usability based on physical damage and empirically derived *usability ratios*
evaluateBuildingOccupancy	Determines building occupancy based on the number of households per building and the land use plan
evaluateBuildingHabitability	Determines building habitability based on usability and residual utility service level
evaluateCasualties	Determines number of dead and injured people based on physical damage and empirically derived *lethality ratios*
evaluateDisplacedPopulation	Determines number of people displaced from home based on building habitability
evaluateSupplyRequirements	Determines required amount of good/service based on cell population and demand model. Called by reference node in each system to aggregate demands from tributary cells

- **Building damage/collapse**
  It estimates the physical damage of the buildings after an earthquake. It is strongly dependent on the type of structure analysed and it describes the probability of a structure to exceed different limit states (such as different level of damage) given a level of ground shaking;
- **Building usability**
  It identifies the extent to which a building can be used by the inhabitants, and depends mainly on the physical damage to the structure (building damage/collapse).
- **Building habitability**
  It identifies whether the occupants can inhabit the building, and depends on the building usability and the utility loss (to the building).
- **Casualty model.**
  This model leads to indicators that estimate the number of deaths and injuries after an earthquake. It depends both on the type of building and on the number of people that live or reside temporarily in the damaged structure.
- **Debris model**
  This model leads to indicators that estimate the amount of debris following an earthquake. It depends on the building type and on the structural and non-structural damage.

5.3.2 Network Systems

This section includes the systems that can be defined as an organized set of edges and nodes: as defined in Chap. 2, networks can be subdivided in two abstract classes, i.e. *Undirected* graphs for utility networks (i.e. water, electric power and gas supply) and *Directed* graphs for transportation networks (i.e. roadways and railways).

5.3.2.1 Water Supply and Waste-Water Systems

The following paragraphs are devoted to the specification of the Water Supply System (WSS), through the description of its class structure, interactions with other systems and possible approaches for performance assessment.

Structure of the System and Input Attributes

The water-supply system as a whole is composed of a number of point-like critical facilities (Water sources, Treatment plants, Pumping stations, Storage tanks) and of the Water distribution network itself. The internal logic of the critical facilities and their function in the management of the whole system should be modelled explicitly. The network portion of the system is made of pipelines, tunnels and canals and the supervisory control and data acquisition (SCADA) sub-system.

The identified system components are:

WSS01:	Source (Springs, shallow or deep wells, rivers, natural lakes, and impounding reservoirs)	[Points]
WSS02:	Treatment Plant	[Points, critical facility]
WSS03:	Pumping station	[Points, critical facility]
WSS04:	Storage Tank	[Points]
WSS05:	Pipe	[Edges]
WSS06:	Tunnel	[Edges]
WSS07:	Canal	[Edges]
WSS08:	SCADA system	[System]

The structure of the Water supply system and the main input attributes are detailed in Fig. 5.2 and Table 5.4.

The waste-water system as a whole is composed of a number of point-like critical facilities (Treatment Plants, Pumping Stations) and of the distribution network itself (Pipelines, Tunnels). The internal logic of the critical facilities and their function in the management of the whole system should be modelled explicitly.

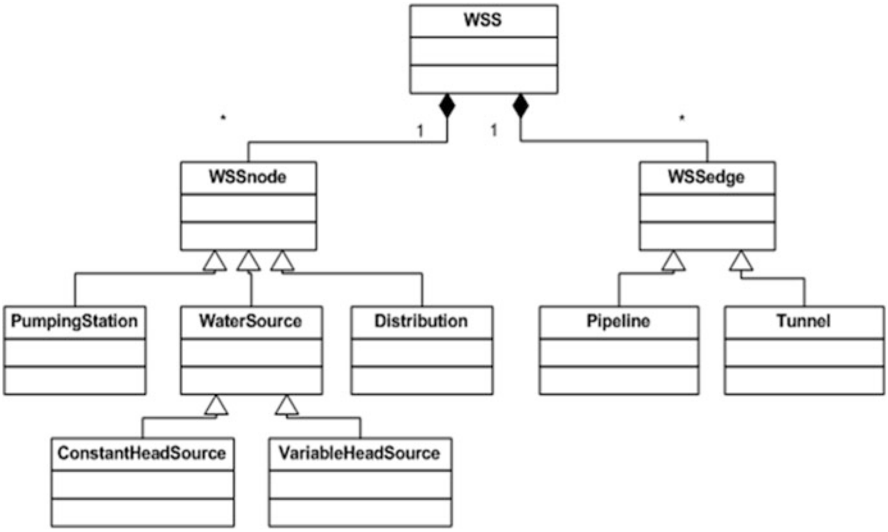

Fig. 5.2 UML class-diagram of the Water Supply System

The identified system components are:

WWN01:	Waste-water treatment plant	[Points, critical facility]
WWN02:	Pumping (lift) station	[Points, critical facility]
WWN03:	Pipelines	[Edges]
WWN04:	Tunnels	[Edges]
WWN05:	SCADA system	[System]

5.3.2.2 Interdependencies

The water supply system is strongly interconnected with the other systems. Most components of the WSS are dependent on the power supply and they are in turn used to feed inhabited areas and health-care centers.

- **EPN ➔ WSS [Physical]:**
  Damage to the EPN can reduce the functionality of pumping stations in the WSS.
- **WSS ➔ BDG [Physical]:**
  Damage to the WSS can lower the service level in the struck area, possibly below tolerance thresholds thus leading to population displacement and demand on the Shelter model.

Table 5.4 Main attributes/properties of the Water Supply System class

Group	Attribute(s)	Description
Global properties	sourceHead	Water head at source nodes
	endUserDemand, hydricEquipment	Required water flow at demand nodes, either assigned or evaluated by aggregating over tributary cells, employing population and hydricEquipment for the region (expressed in [l/inhab./day])
	refEPNnode	Pointers to EPN node(s) feeding power to pumping stations (for inter-dependence modelling)
Pointers	pipe	Pointers to all the pipes in the system, objects from the pipe class
	demand	Pointers to all end-user nodes, objects from the DistributionNode class
	source	Pointers to all sources in the system, in general objects from the ConstantHeadSource and VariableHeadSource (for finite reservoirs) classes
	pump	Pointers to all pumping station nodes, objects from the PumpStation class
Edge properties stored at WSS level	edgeMaterial, edgeDiameter, edgeRoughness, edgeDepth	Length, centroid, etc. are attributes inherited from the Network class. Here the network-specific properties are listed (roughness, diameter, laying depth, etc.)
Node properties stored at WSS level	nodeMinimalHead	Minimal head required at nodes for delivery of the assigned demand water flow; this property is a function of the average building elevation in the region of interest
	nodeDepth	–
State variables recording WSS state	states	$n_E \times 1$ collection of properties that describe the current state for each of the n_E events (fields: demandFlow, outFlow, average head ratio, system serviceability index, number of leaks, number of breaks, etc.)

- **WSS ➔ HCS [Physical]:**
  Damage to the WSS can prevent water from being delivered to the health-care facilities, hindering emergency response over time in case backup reservoirs are depleted.

5.3.2.3 Methods for Systemic Analysis

The seismic reliability of water networks can be assessed using different indices of physical nature like vulnerability, connectivity, serviceability, maximum flow, redundancy, or immaterial estimates like economic loss (ATC 1991).

Connectivity analyses measure the post-earthquake integrity of the system, i.e., the extent to which links and nodes are still connected. Serviceability analyses estimate the post-earthquake capacity between selected source-to-sink nodes. Serviceability is a performance measure that considers mostly the hydraulic behaviour of the networks and less the robustness of the network in terms of its layout.

Closely related to reliability is redundancy, a characteristic of the overall system performance that is often neglected. Redundancy in a water supply network determinates the existence of backup capacities and of alternatives for routing, i.e. the existence of additional paths from supply to demand nodes in case of breaks in the main supply links (Awumah et al. 1991). The redundancy of a water supply system can be evaluated along with reliability to assess system performance under earthquake stimulations, in order to design a new network, and for efficient seismic mitigation of the existing network.

Reliability assessment could be performed with the mitigation prioritization procedure. Multi-criteria analysis (MCA) is probably more efficient than traditional cost-benefit analysis, as it copes with the uncertainties inherent to the judgment of experts. Moreover, the model has to consider customers importance, pipeline properties and hazard factors. Hence, to prioritize renewing of the lifeline systems, a fuzzy analytic hierarchy process (FAHP) to support the MCA has advantages. This optimized fuzzy prioritization method can be applied as an evaluation tool (Alexoudi et al. 2009), where uncertain and imprecise judgments of experts are translated into fuzzy numbers.

Seismic risk of water system has been investigated extensively (Ballantyne et al. 1990; Taylor 1991; Shinozuka et al. 1992; Hwang et al. 1998; Shi et al. 2006; Wang 2006). Chang et al. (2002) assessed the seismic risk of the WSS in Memphis, whereas the impacts of the 1906 San Francisco and 1989 Loma Prieta earthquakes on the system reliability of the auxiliary WSS of the city of San Francisco are detailed by Scawthorn et al. (2006). In this paper, the authors also described the induced consequences of the inoperability of some part of the Water system on earthquake-triggered fires.

The methods to address the risk of WSS can be classified as follows:

- **Level 0 (Vulnerability Analysis)**:
  - The scope is to estimate the percentage of the physical damages to the WSS elements in a specific region based on the vulnerability analysis of water network components, which can be estimated through appropriate fragility curves or/and Monte-Carlo technique.
  - The majority of the studies performed for water systems can be categorized as Level 0, implying simple physical vulnerability studies of water system components (ATC 1985; ATC 1991; NIBS 2004). The performance index used in Level 0 studies is the "Damage Ratio" that describes the expected number of failures per unit of length (for pipes), per link or per node of the system. Moreover, the "Damage Ratio" can be considered as a percentage of the damaged nodes/links.

- **Level I (Connectivity Analysis):**
  - In this level of systemic analysis, the concern is the connectivity between functioning supplying nodes (water sources and pumps) to demand nodes (linked to other systems), through undamaged pipes. In order to do that,

the damaged components are removed from the network. Then, some of the remaining nodes which are completely isolated from all supply nodes must be removed from the original network.

– A simple connectivity analysis (Level I) of the network can be accomplished using Graph Theory (clustering coefficient of a graph, Redundancy Ratio, Service Ratio Reachability Ratio) and Statistical Methods (Simple Level I Analysis). Illustration of Advanced Level I studies can be found in Shinozuka et al. (1977) and O'Rourke et al. (1985), which use minimal cut set paths in reliability evaluation of lifeline networks. Moreover, available techniques to identify the minimal paths and minimal cut sets have mainly been presented in literatures as connectivity analyses of the network (Jasmon and Kai 1985; Fotuhi-Firuzabad et al. 2004). Another example of Level I analysis is the study performed by Kawakami (1990), which uses the "Damage Ratio" (Level 0) and "Service Ratio" (Level I) as performance indices. Service Ratio indicates the ratio of normally supplied houses over the total number in the system. Dueñas-Osorio et al. (2007a) propose the concept of "Connectivity Loss" in order to quantify the average decrease of the ability of distribution vertices to receive flow from the generation vertices. Dueñas-Osorio et al. (2007b) introduce "Redundancy Ratio" as the appropriate parameter to measure the performance of water system. Moghtaderi-Zadeh et al. (1982) propose "*Reachability*" of water as performance index, indicating the probability that a certain amount of water flow would reach key locations (nodes). Conclusively, "*Damage Ratio*", "*Service Ratio*", "*Connectivity Loss*", "*Redundancy Ratio*" and "*Reachability*" are the performance indicators used in such level of analysis (Level I).

- **Level II (Flow Analysis/Serviceability Analysis):**

  – At this level, the concern is the quantity of the water provided to the user and the ability of the system to meet the needs. The physical-based indicators such as water head, flow rate and amount of leakage at each demand node are calculated under intact (pre-earthquake) conditions. Equivalent physical-estimates are assessed for pipes, like the quantity of flow and head loss. After the evaluation of the physical damages to the pipes (break, leak), a flow analysis is performed involving the newly formed "damaged" network. It is assumed that, when a pipe is broken, a shutdown device is automatically activated to prevent water leakage in pipe. Another underlying hypothesis is the unchanged capacity of the supplying nodes. Vulnerability and damage estimations of water system components, with the resulting flow analysis can be repeated for different seismic intensities using Monte-Carlo simulations. Average values of the flow rate and water pressure are then calculated at each node, and these values are compared to the measures for normal (pre-earthquake) conditions. The results are generally returned as ratios of post- to pre- earthquakes measures, and given in percentage of reduction of functionality.

– Many researchers have contributed to the improvement of seismic reliability methods for water supply systems from the flow and serviceability analysis viewpoint (Level II) (e.g. Shinozuka et al. 1981; Isoyama and Katayama 1981; O'Rourke et al. 1985; Javanbarg and Takada 2009). One example of Level II study is the one performed by Shinozuka et al. (1981). Their methodology allowed assessing the seismic reliability of water supply system in Los Angeles regarding the serviceability. The condition to consider the system serviceable is the remaining intact capabilities of fire-fighting systems after the earthquake. Monte Carlo simulations were carried out in order to estimate the probability of serviceability levels on the basis of estimated physical damage states of the elements of system at the aftermath of an earthquake. O'Rourke et al. (1985) also simulated the consequences of an earthquake on the serviceability of the water supply system in city of San Francisco through a flow analysis. The considered performance indicator for their analysis was the ratio of available water flow over the required one at a given and requested pressure at proximity to the fire outbreak (Level II). Potential performance indices used in Level II analyses include the probabilistic distribution of the percentage of customers who would lose their service after a specific earthquake.

These approaches require complex hydraulic analyses, which are time consuming and require expertise and availability of extensive data. For this reasons, a number of researchers have developed simplified models to assess the serviceability of pipeline networks under various amounts of pipe damages (Markov et al. 1994; Hwang et al. 1998; Javanbarg et al. 2006 and Shi et al. 2006). HAZUS (NIBS 2004) methodology proposes a diagram correlating the Serviceability Index (SI) (see Sect. 5.3.2.1 for definition) to average break rate (i.e. the number of complete failure of the pipeline section per unit of length).

Besides the models classified in the above three categories (Level 0 to II), other models have been also proposed, such as redundancy approaches (Awumah et al. 1991; Kalungi and Tanyimboh 2003; Hoshiya and Yamamoto 2002; Hoshiya et al. 2004) and studies for the identification of critical links of water supply systems under earthquakes (Wang et al. 2010).

The main UML-methods corresponding to these 3 levels of analysis used in the SYNER-G approach are described in Table 5.5 and their applications are detailed in Chaps. 7 and 8.

Over the last twenty years, waste-water systems worldwide have also been heavily damaged by natural disasters such as earthquakes. The societal and economic disruption caused by waste-water network damages is important, as for example, the impact on public health and environment due to the discharge of raw/inadequately treated sewage.

The required effort to assess the performance of waste-water systems varies with the level of analysis and the complexity of the system. Most of the available methodologies used for waste-water systems, estimate the physical damages, the replacement cost and the restoration time of the system's component without

Table 5.5 Most relevant UML-methods of the Water Supply System class

Method	Description
computeDemand	Aggregates demand from tributary cells in demand nodes
isBreakAndLeaksNumber	Evaluates the damage state of each pipeline segment employing the corresponding set of fragility functions and the current intensity at the centroid
computeLeakageArea	Computes the amount of leakage from the numbers of leaks in each pipe segment
updateConnectivity	Updates the adjacency matrix based on the pipe breaks and/or the failure of the nodes (e.g. pumping stations, reservoirs)
computeFlow	Computes the actual flow from the sources to the demand nodes based on an optimization algorithm, using the demand level and the leakage amount
computePerformanceIndicator	Computes the different PIs at component- and system-level

considering the overall performance of the network (ATC 1991; ATC 1985; NIBS 2004). While this system has been fully addressed in the SYNER-G project, its systemic evaluation should follow the same approach as for the water supply network.

5.3.2.4 Performance Indicators

Component-Level Performance Indicators (PIs)

- *Junctions/Nodes:* **Head Ratio**, or HR. ***[Level II]***

For each node, this index is defined as the ratio of the water head in seismically damaged network (H_{si}) over the reference value for the non-seismic, normal operations conditions (H_{0i}):

$$HR_i = H_{si}/H_{0i} \tag{5.1}$$

The determination of the water head requires a flow analysis of the network. Hence this index expresses the functional consequence in the i-th component of the physical damage to all system components (within the WSS). When interactions with other systems are modeled, HR_i expresses the functional consequence in the i-th component of the physical damage to components of the other systems (WSS, EPN, etc.), i.e., it is the value of the index that changes due to the inter- and intra-dependencies, not its definition.

- *Pipes:* the **Damage Consequence Index**, or DCI. ***[Level II]*** (Wang et al. 2010)

This index measure the impact of each pipe on the overall system serviceability and identify critical links that significantly affect the system's seismic performance. The index is defined at the component level in terms of a system-level PI that measures serviceability; the System Serviceability Index (*SSI*) is defined afterwards. Thus, as for the HR index, this is a PI that reflects at component-level the functional consequence of damage to all systems' components and incorporates the effect of the inter- and intra-dependencies, when modelled. The *DCI* for the *i*-th pipe is defined to reflect the consequence from damaging the pipe, including pipe breaks and leaks. It is expressed as:

$$DCI_i = \frac{E\,[SSI] - E\,[SSI\,|L_i\,]}{1 - E\,[SSI]} \tag{5.2}$$

in which *E[SSI]* is the (unconditional) expected value of *SSI* from a set of simulations in which the *i*-th pipe might or might not be damaged; and *E[SSI|Li]* is the conditional expectation of *SSI* from another set of simulations under the same seismic hazard, but given that the *i*-th pipe is damaged.

- *Pipes:* **Upgrade Benefit Index**, or UBI. ***[Level II]*** (Wang et al. 2010)

Similarly to the *DCI*, this index measures the impact of an upgrade of an individual pipe on the overall system serviceability, and reflects at the component level the systemic functional consequence of damage to the whole system(s). It is defined as:

$$UBI_i = \frac{E_{upgrade}\,[SSI] - E\,[SSI]}{1 - E\,[SSI]} \tag{5.3}$$

in which $E_{upgrade}[SSI]$ is the expected value of *SSI* given that the *i*-th pipe is "upgraded." By "upgrade", it is meant that the probability of pipe damage given an earthquake is significantly smaller than its value before upgrade. UBI_i is the percent increase of *SSI* given that the *i*-th pipe is upgraded, and its relative value is a measure of the pipe impact on the overall system serviceability.

System-Level Performance Indicators (PIs)

- **Average Head Ratio**, or AHR. ***[Level II]***

This index is defined as the average over the network nodes of the *HR* index:

$$AHR = \overline{HR} = \frac{1}{n_N}\sum\nolimits_{i=1}^{n_N} HR_i \tag{5.4}$$

where n_N is the number of nodes in the WSS.

- **System Serviceability Index**, or SSI. ***[Level II]*** (Wang et al. 2010).

The System Serviceability Index is defined as the ratio of the sum of the satisfied customer demands after an earthquake over the ones before the earthquake:

$$SSI = \frac{\sum\nolimits_{i=1}^{n} Q_i}{\sum\nolimits_{i=1}^{n_0} Q_i} \tag{5.5}$$

where n and n_0 are the number of satisfied demand nodes after and before the earthquake, and Q_i is the demand at the i-th node. The *SSI* varies between 0 and 1.

A single value can be determined for a given condition of the network. Its probabilistic characterization, in terms of either its full distribution or its expected value *E[SSI]* that enters in the definitions of *DCI* and *UBI*, requires running multiple simulations for different earthquake realizations. The above definition from Wang et al. (2010) assumes that the demand remains fixed before and after the earthquake, since it looks only at a single system, without considering the interactions of the WSS with the other systems.

Finally, regarding waste-water systems, ALA (2004) proposes different performance indicators like (i) capacity measures (e.g. flow of waste-water at selected points); (ii) measures of reliability (such as frequency and magnitude of sanitary sewer overflows (SSOs) or combined sewer overflows (CSOs), and the frequency and magnitude of discharge of inadequately treated sewage, percentage treated, etc.); (ii) measures of safety and health (backup of any raw sewage into buildings-not acceptable, overflow of raw sewage into streets-acceptable in localized areas for less than 24 h); or (iv) financial measures. The Environmental Protection Agency National Pollution Discharge Elimination System (EPA NPDES) permit requirements incorporate relevant performance measures such as discharge volume and water quality.

5.3.2.5 Gas and Oil Networks

This section focuses on the systems that are in charge of the delivery of natural gas and oil from production/gathering facilities to inhabited areas, especially the transmission/distribution network and the related support stations (i.e. for compression/reduction of the hydrocarbon flows).

Structure of the System and Input Attributes

The natural gas or oil system as a whole is composed of a number of point-like critical facilities (Production and gathering facilities, Treatment plants, Storage facilities, Intermediate stations where gas is pressurized/depressurized or simply metered) and of the transmission/distribution network itself. The internal logic of the critical facilities and their function in the management of the whole system should be modelled explicitly. The network portion of the system is made of edges (i.e. pipelines) and of the supervisory control and data acquisition (SCADA) sub-system.

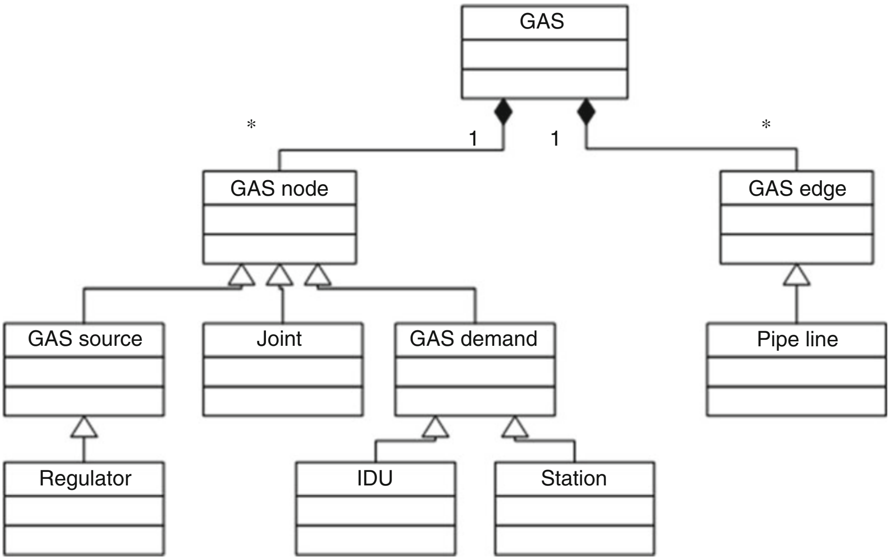

Fig. 5.3 UML class-diagram of the Gas Network System (Esposito and Iervolino 2012). IDU class represents the end-user nodes (i.e. final node for low-pressure networks)

For the GAS system the identified components are:

GAS01:	Production and gathering facility (Onshore, Offshore)	[Points, critical facility]
GAS02:	Treatment plant	[Points, critical facility]
GAS03:	Storage tanks	[Points]
GAS04:	Station (Compression, Metering Compression/ metering, Regulator/metering)	[Points, critical facility]
GAS05:	Pipelines	[Edge]
GAS06:	SCADA	[Systems]

For the OIL system the identified components are:

OIL01:	Production and gathering facility (Onshore, Offshore)	[Points, critical facility]
OIL02:	Refinery	[Points, critical facility]
OIL03:	Storage tank farm	[Points]
OIL04:	Pumping Station	[Points, critical facility]
OIL05:	Pipelines	[Edges]
OIL06:	SCADA	[Systems]

The object-oriented structure and the main class attributes of the Gas network system are presented in Fig. 5.3 and Table 5.6.

Table 5.6 Main attributes/properties of the Gas Network System class

Group	Attribute(s)	Description
Global properties	sourceHead	Gas pressure at source nodes
	endUserDemand	Required gas pressure at demand nodes, either assigned or evaluated by aggregating over tributary cells, employing population for the region
	refEPNnode	Pointers to EPN node(s) feeding power to compression/reduction stations (for inter-dependence modelling)
Pointers	pipe	Pointers to all the pipes in the system, objects from the Pipe class
	demand	Pointers to all end-user nodes, in general objects from the IDU (low-pressure network) or the Station (medium-pressure network) classes
	source	Pointers to all sources in the system, objects from the GASsource class
	station	Pointers to all compression/reduction stations in the system, objects from the Station class
	joint	Pointers to all joint nodes in the system, to reproduce the geometry of the network system, objects from the Joint class
Edge properties stored at GAS level	edgeMaterial, edgeDiameter, edgeRoughness, edgePressure	Length, centroid, etc. are attributes inherited from the Network class. Here the network-specific properties are listed (roughness, diameter, operating pressure, etc.)
Node properties stored at GAS level	fragility	Fragility type for Station objects
State variables recording GAS state	states	$n_E \times 1$ collection of properties that describe the current state for each of the n_E events (fields: demandFlow, outFlow, average pressure ratio, system serviceability index, number of leaks, number of breaks, etc.)

5.3.2.6 Interdependencies

Interactions of gas and oil networks with other systems are mainly of physical nature, since it is based on the supply of hydrocarbons to the customers.

+ Natural Gas System

- **EPN → GAS [Physical]:**
  Damage to the EPN can hinder the proper operation of re-gasification and regulation/metering stations in the GAS system.
- **GAS → BDG [Physical]:**
  Damage to the GAS system can lower the service level in the struck area, possibly below tolerance thresholds, especially in adverse weather conditions, thus potentially leading to population displacement.

- **GAS ➔ HCS [Physical]:**
  Damage to the GAS system can prevent natural gas to be fed to the health-care facilities hindering emergency response in case backup power sources depend on gas fuel.

+ Oil System

- **EPN ➔ OIL [Physical]:**
  Damage to the EPN can prevent functioning of stations in the OIL system.
- **OIL ➔ EPN [Physical]:**
  Damage to the OIL system can stop production in generators within the EPN inducing power shortages.

5.3.2.7 Methods for Systemic Analysis

The selected works referenced in this section can be classified based on the different goals that the network is expected to meet and the approach used for the network analysis.

+ Natural Gas System

Depending on the purpose of the study, three levels of analysis can be used for the evaluation of seismic performance of gas networks.

- **Level 0 (Vulnerability analysis):**
  - Level 0 analysis is a basic vulnerability analysis and it is related to the physical performance of a single component of the network (e.g. for a gas system it could involve the number of breaks per kilometre for the pipeline system).
- **Level I (Connectivity analysis):**
  - Level I analysis is related to the existence of a path connecting sources and the demand nodes, when the links and the nodes may fail (Ching and Hsu 2007), allowing the assessment of *serviceability*, for example in terms of the number of distribution nodes which remain accessible from at least one supply node after the earthquake (Adachi and Ellingwood 2008; Poljanšek et al. 2012).
- Connectivity analysis requires a simple description of the network in terms of a graph, defined as a collection of nodes (i.e., stations) and links (i.e., pipes) connecting nodes. Moreover, in order to perform the connectivity analysis, nodes should be distinguished considering their functionality. Connectivity analysis tools are limited to those of graph theory (e.g. Ching and Hsu 2007). These algorithms are applied on the network after removing the parts of the system that are failed after the seismic event.
- **Level II (Flow analysis):**
  - Flow analysis includes consideration of the network's capacity, for example maintaining minimum head pressure related to leakages from two particular

Table 5.7 Most relevant methods of the Gas Network System class

Method	Description
computeDemand	Aggregates demand from tributary cells in demand nodes
isBreakAndLeaksNumber	Evaluates the damage state of each pipeline segment employing the corresponding set of fragility functions and the current intensity at the centroid
computeLeakageArea	Computes the amount of leakage from the numbers of leaks in each pipe segment
updateConnectivity	Updates the adjacency matrix based on the pipe breaks and/or the failure of the nodes (e.g. pumping stations, sources)
computePressure	Computes the actual pressure from the sources to the demand nodes based on an optimization algorithm, using the demand level and the leakage amount
computePerformanceIndicator	Computes the different PIs at component- and system-level

points of the network or related to a demand node (Li et al. 2006; Helseth and Holen 2006). In flow analysis, the network's performance is measured evaluating the satisfied end user demand, in terms of flow, after the earthquake event with respect to that before the earthquake. For the purpose of calculating pipe flow and nodal pressure before and after the seismic event, it is necessary to consider flow equations and a method to solve the network analysis problem (Osiadacz 1987).

In the SYNER-G framework, the main UML[1]-methods used to solve the gas network system are described in Table 5.7. An application of these functions is described in Chap. 9.

+ Oil system

The UML-methods used in the vulnerability assessment of natural gas systems can be also applied to oil systems. The classification mentioned above can therefore be used here too.

5.3.2.8 Performance Indicators

Performance indicators are defined to estimate the performance of the system at component or system-level, for the different level of analysis.

Component-Level Performance Indicators (PIs)

- *Pipelines:* **Damage Consequence Index** or DCI. ***[Level II]*** (Wang et al. 2010)

This index is defined at the component level in terms of a system-level PI that measures serviceability; the System Serviceability Index (*SSI*) is defined afterwards.

[1]UML: Unified Modeling Language.

Thus, as for the HR index, this is a PI that reflects at component-level the functional consequence of damage to all systems' components and incorporates the effect of the inter- and intra-dependencies, when modelled. The *DCI* for the *i*-th pipe is defined to reflect the consequence from damaging the pipe, including pipe breaks and leaks. It is expressed as:

$$DCI_i = \frac{E\,[SSI] - E\,[SSI\,|L_i\,]}{1 - E\,[SSI]} \tag{5.2}$$

in which *E[SSI]* is the (unconditional) expected value of *SSI* from a set of simulations in which the *i*-th pipe might or might not be damaged; and *E[SSI|Li]* is the conditional expectation of *SSI* from another set of simulations under the same seismic hazard, but given that the *i*-th pipe is damaged.

- <u>*Nodes:*</u> Pressure Ratio or PR. *[Level II]*

The Pressure Ratio is defined, for each node, as the ratio between the gas pressure at the *i*-th node, in the seismically damaged network, P_{si}, and the reference value of the pressure P_{oi}, for normal operating conditions. The determination of the gas pressure in the seismically damaged network, P_{si} requires a flow analysis of the network.

$$PR_i = \frac{P_{si}}{P_{0i}} \tag{5.6}$$

- <u>*Demand Nodes*</u>: **Customer Connectivity** or CC. ***[Level I]***

The Customer Connectivity evaluates the capacity of demand nodes (or stations) in the gas distribution network to satisfy customers receiving flow from supply nodes (stations or plants). *CC* counts the number of customers satisfied by the *i*-th demand node $N^i_{customer,s}$ if the *i*-th demand node is accessible from at least one supply node, with respect to the number of customers in the undamaged network $N^i_{customer,0}$ Moreover this index can be evaluated for each type of customer, i.e. residential, industrial or strategic:

$$CC_i = \frac{\mathrm{N}^{\mathrm{i}}_{\mathrm{customer,s}}}{\mathrm{N}^{\mathrm{i}}_{\mathrm{customer,0}}} \tag{5.7}$$

System-Level Performance Indicators (PIs)

- **System Serviceability Index** or SSI. ***[Level II]*** (Wang et al. 2010)

Originally defined by Wang et al. (2010) for a Water Supply System, the System Serviceability Index is proposed as a system performance indicator for the Gas and Oil networks. The *SSI* is a relative index that compares the serviceability of the utility network, in terms of customer demand satisfaction, before and after the earthquake. The description of this indicator can be found in Sect. 5.3.2.1.

- **Connectivity Loss** or CL. ***[Level I]*** (Poljanšek et al. 2012)

Connectivity loss (CL) measures the average reduction in the ability of sinks (e.g. gas-fired power plants or distribution nodes for inhabited areas) to receive flow from sources (gas fields and LNG terminals) by counting the number of the sources connected to the *i*-th sink in the original (undamaged) network $N^i_{source,0}$ and then in the damaged network $N^i_{source,s}$.

$$CL = 1 - \left\langle \frac{N^i_{source,0}}{N^i_{source,s}} \right\rangle_i \tag{5.8}$$

- **Serviceability Ratio** or SR. ***[Level II]*** (Adachi and Ellingwood 2008)

The Serviceability ratio, originally defined by Adachi and Ellingwood (2008) for Water Supply Systems, is also proposed for Gas and Oil systems. This index is directly related to the number of distribution nodes in the utility network, which remain accessible from at least one supply facility following the earthquake. It is computed as:

$$P\left[SR \le s\right] = P\left[SR \le \frac{\sum_{i=1}^{N} w_i X_i}{\sum_{i=1}^{N} w_i}\right] \tag{5.9}$$

Where SR is the serviceability ratio of the system defined on the domain [0;1], w_i is a weighting factor assigned to the distribution node *i* and X_i represents the functionality of the node *i*, which is modeled as the outcome of a Bernoulli trial ($X_i = 1$ if the node is accessible from at least one supply facility) and N is the number of distribution nodes.

- **Average Pressure Ratio** or APR. ***[Level II]***

The Average Pressure Ratio is defined as the average ratio of the gas pressure in the seismically damaged network over the reference value for non-seismic, normal operations conditions considering n_N nodes.

$$APR = \frac{1}{n_N} \sum_{i=1}^{n_N} PR_i \tag{5.10}$$

Where PR_i is the pressure ratio defined above.

- **Utility Customer density.** ***[Level I]***

The Utility Customer Density measures the average number of customers connected to the utility services per square kilometre at the certain time. It can be evaluated considering the type of customer, i.e. residential, industrial or strategic.

5.3.2.9 Electric Power Network

The focus is put here on the electric power transmission network, from the power generators to the distribution substations.

Structure of the System and Input Attributes

The Electric-power system as a whole is composed of a number of point-like critical facilities (Power generation facilities, Transformation substations, Maintenance facilities) and of the Electric power transmission network itself. The internal logic of the critical facilities and their function in the management of the whole system should be modelled explicitly. The network portion of the system is made of lines and of the supervisory control and data acquisition (SCADA) subsystem.

The identified system components are:

EPN01:	Electric power grid	[System]
EPN02:	Power plant	[Points, critical facilities]
EPN03:	Sub-station (distribution, transformation-distribution)	[Points, critical facilities]
EPN04:	Distribution circuits	[Points, critical facilities]
EPN05-23:	Substation Components	[Points, critical facilities]
EPN24:	Transmission or distribution line	[Edges]

The Electric Power Network is described in terms of objected-oriented structures (Fig. 5.4) and the corresponding attributes (Table 5.8).

5.3.2.10 Interdependencies

The Electric Power Network is a key component of critical infrastructures and it is at the basis of the operation conditions of almost all other systems.

- **EPN ➔ BDG [Physical]:**
  Damage to the EPN can lower the service level in the struck area, possibly below tolerance thresholds thus potentially leading to population displacement.
- **EPN ➔ WSS [Physical]:**
  Damage to the EPN can prevent functioning of pumping stations in the WSS.
- **EPN ➔ GAS [Physical]:**
  Damage to the EPN can prevent functioning of re-gasification and regulation/metering stations in the GAS system.
- **EPN ➔ OIL [Physical]:**
  Damage to the EPN can prevent functioning of stations in the OIL system.

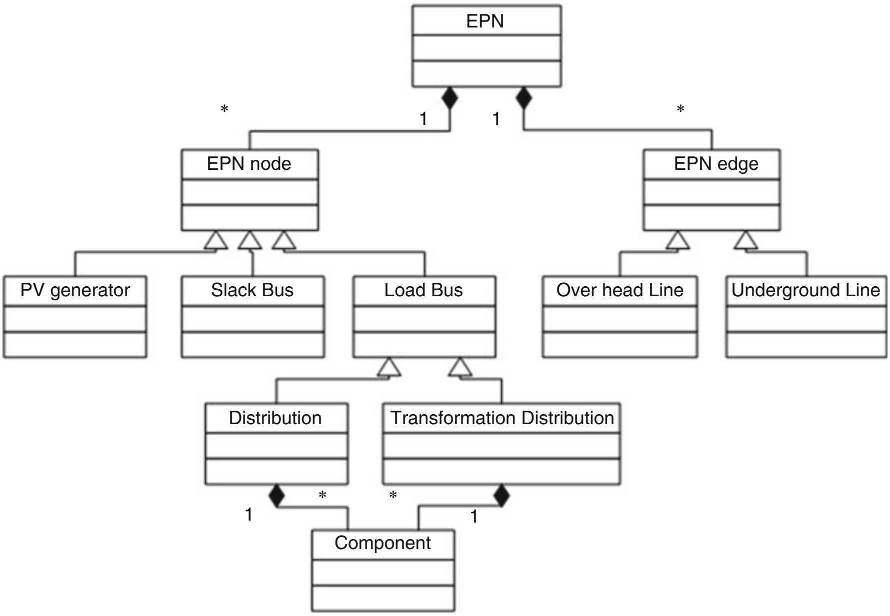

Fig. 5.4 UML class-diagram of the Electrical Power Network (EPN)

- **EPN ➔ HBR [Physical]:**
  Damage to the EPN can prevent functioning of critical components in the HBR system.
- **EPN ➔ HCS [Physical]:**
  Damage to the EPN can prevent power to be fed to the health-care facilities hindering emergency response in case a joint failure of backup power sources occur.

5.3.2.11 Methods for Systemic Analysis

Damages following recent earthquakes revealed that electric power supply, one of the most important services that need to be guaranteed after an earthquake, is maybe the least reliable function. Examples include earthquakes in many countries worldwide: after the earthquake of Kocaeli, Turkey, in 1999, the half of the region's hospitals were not supplied with electricity; about the same happened in Kobe, Japan, 1995, when the whole area was isolated for a period from three to five days; in Northridge, U.S.A., 1994, the electric isolation lasted a day; other earthquakes, even of moderate intensity, caused severe damage either to the entire network, preventing power flow, or to single stations, isolating single nodes.

There are many reasons for carrying out a seismic vulnerability analysis of an EPN. First, the construction of electric networks in industrialized countries, dates

Table 5.8 Main attributes/properties of the Electric Power Network class

Group	Attribute(s)	Description
Global properties	endUserDemand	Required power level at demand nodes, either assigned or evaluated by aggregating over tributary cells, employing population for the region
	admittanceMatrix	Admittance matrix of the EPN, containing the self and mutual bus admittances
Pointers	line	Pointers to all the transmission lines in the system, objects from the EPNLink class
	slack	Pointers to the slack bus, one object from the SlackBus class
	generator	Pointers to all power generators (excluded the slack bus) in the system, objects from the PVGenerator class
	transdistr	Pointers to all transformation/distribution substations in the system, objects from the TransformationDistribution class
	distribution	Pointers to all distribution substations in the system, objects from the Distribution class
Edge properties stored at EPN level	voltage, resistance, voltageRatio	Length, centroid, etc. are attributes inherited from the Network class. Here the network- specific properties are listed (voltage range, etc.)
Node properties stored at EPN level	busType	Typology of the bus that is used to assign a given fragility function, as well as the role in the network
State variables recording EPN state	states	$n_E \times 1$ collection of properties that describe the current state for each of the n_E events (fields: busDown, isolatedBus, shortCircuitIn, shortCircuitOut, VoltageRatio, etc.)

back to a period when earthquake engineering was not at an advanced stage: priority was naturally given to electrical issues when designing components, and thus the equipment currently in place within the stations is not designed for seismic forces. Further, for many types of equipment, the most effective electrical configuration (a slender vertical beam, with steel below, ceramic above and heavy equipment on top) happened to be the least effective structural configuration. Moreover, short-circuits may spread from one station to another, thus isolating large parts of the network.

It should be noted, however, that for a widely distributed and redundant network, damage to a few of the network components will not necessarily lead to a widespread power black-out as a result of alternative paths within the system. Also, as a result of its redundancy, the seismic performance and reliability of an electric power transmission system may be enhanced by upgrading just a few of the network components (Shumuta 2007). Quantitative (probabilistic) information on the likelihood of different levels of damage and extent of affected areas under different earthquake intensities would, therefore, be worthwhile for determining the necessary upgrading of an existing system and for emergency planning and disaster reduction preparedness, including restoration of power.

Economic and social consequences arising from direct and indirect losses due to seismic failures in the EPN are huge, since post-emergency civil protection operations, hospitals, telecommunications, industries and other functions are all affected.

Seismic behaviour of electric power network thus appears a rewarding field of research; however, the efforts on this subject have been limited as compared to other topics. This is probably due to the fact that electric networks more naturally fall within the expertise of electrical engineers, and also to intrinsic complexity in modelling, requiring advanced mathematical tools and interdisciplinary knowledge.

The analysis of an EPN in a seismically active environment can be carried out, as for other lifeline systems, at three different levels.

- **Level 0 (Vulnerability analysis):**
  - Level 0 analysis is a basic vulnerability analysis and it is related to the physical performance of a single component of the network (e.g. power plants, substations, lines . . .)
- **Level I: Connectivity analysis.**
  - Connectivity-based methods focus on finding connected components within the network so that supply and demand can be connected. In their basic form, the methods only lead to a binary statement on whether any given node is connected with another node, specifically a source node, through the network.
  - Li and He (2002) and Kim and Kang (2013) used a non-simulation-based network reliability method, the Recursive Decomposition Algorithm, for risk assessment of generic networks whose operation is defined by the connections of multiple initial and terminal node pairs. Kang et al. (2008) proposed another non-simulation-based method, the Matrix-based System Reliability method, which is able to compute the probability of general system events (at the connectivity level) with correlated system components based on efficient matrix manipulations and minimal set identification.

    Dueñas-Osorio and Rojo (2011) introduced a closed form technique to obtain the entire probability distribution of a reliability metric of customer service availability (CSA) for generic radial lifeline systems. Further works falling within the framework of complex system theory are those by Arianos et al. (2009) and Bompard et al. (2011 The work by Buritica et al. (2012) also relies on a hierarchical representation of networks, the Markov Clustering Algorithm (Gomez et al. 2011), which uses the affinity matrix and random walks to simulate flow through the network and identify communities.
- **Level II (Capacity Analysis)**
  - Capacity analysis is based on the power flow analysis and the point that the actual electrical quantities (voltages, currents, powers) in the network nodes and lines must be determined to make any meaningful statement on the

satisfaction of the power demand at the node, not just its state of continued connectivity. The latter is an intrinsically systemic problem since it depends on the determination of the flows on the entire (damaged) network. Further, before being able to evaluate flows it is necessary to determine which EPN portion remains functional after an event.

– Dueñas-Osorio and Vemuru (2009) included in their reliability assessment study the analysis of flow dynamics, thus allowing to capture the possibility that the system undergoes large-scale cascading failures, the latter being caused by flow redistribution after the occurrence of disruptive events. Pires et al. (1996) presented a simulation-based model to evaluate the seismic reliability of electric power transmission systems, allowing estimating the probability of disconnection of substations from supply nodes, as well as the probability of abnormal power flow in substations. These latter facilities are considered as series systems of a number of electrical components, characterized each by a fragility function.

Some authors (Vanzi 1995, 1996, 2000; Giannini and Vanzi 2000; Nuti et al. 2007) did not simply consider the network nodes (buses) as points characterized by a unique fragility function; rather, they modelled the substations' internal logic. In this model, seismically-induced damage to the components of a substation can have non-local consequences, leading to a short-circuit that may or may not propagate within the substation and eventually further away from that substation to adjacent others, generating in extreme cases very large black-outs. In the analysis of short-circuit propagation, circuit breakers are the only active components playing a key role in arresting the short-circuit spreading. This model allows for intermediate non-binary states to be captured.

Among the "probability-based" vulnerability assessment methods, Ma et al. (2010) proposed a method to evaluate the power system vulnerability in terms of voltage magnitudes and transmission lines passing their limits; a probabilistic technique is applied to obtain the PDF and CDF of the voltage magnitude and transmission line power flows. Xingbin and Singh (2004) employed the power flow computation within an integrated scheme to study the power system vulnerability considering protection system failures.

The three types of level analysis are implemented in SYNER-G, and used according to the levels of the available data and requested details. The corresponding UML-methods implemented are detailed in Table 5.9 and an application of an analysis of the EPN is provided in Chap. 10.

5.3.2.12 Performance Indicators

Performance indicators are defined to estimate the performance of the Electrical Power Network at component or system-level, for the aforementioned different level of analysis.

Table 5.9 Most relevant UML-methods of the Electric Power Network class

Method	Description
computeDemand	Aggregates demand from tributary cells in demand nodes
computeDamage	Evaluates the damage state of each station/bus employing the corresponding set of fragility functions and power loss
spreadShortCircuitsInStation	Computes the short-circuit propagation
checkStationDamage	Deletes the transmission lines affected by short circuits
computePerformanceIndicator	Computes the different PIs at component- and system-level

Component-Level Performance Indicators (PIs)

- **Damage Consequence Index**, or DCI [Level II] (Wang et al. 2010)

  Same as for WSS (Sect. 5.3.2.4)

  This index is defined at the component level in terms of a system-level PI that measures serviceability, the System Serviceability Index (SSI), defined afterwards. Thus, as for the HR index, this is a PI that reflects at component-level the functional consequence of damage to all systems' components (and incorporates the effect of the inter- and intra-dependencies, when modelled). The DCI for the *i*-th element is defined to reflect the consequence from damaging the element *i*. It is expressed as:

$$DCI_i = \frac{E\left[SSI\right] - E\left[SSI\,|L_i\,\right]}{1 - E\left[SSI\right]} \tag{5.11}$$

in which *E[SSI]* is the (unconditional) expected value of *SSI* from a set of simulations in which the *i*-th pipe might or might not be damaged; and *E[SSI|Li]* is the conditional expectation of *SSI* from another set of simulations under the same seismic hazard, but given that the *i*-th pipe is damaged.

- **Upgrade Benefit Index**, or UBI [Level II] (Wang et al. 2010)

  Same as for WSS (Sect. 5.3.2.4)

  Similarly to the *DCI*, this index measures the impact of an upgrade of an individual pipe on the overall system serviceability, and reflects at the component level the systemic functional consequence of damage to the whole system(s). It is defined as:

$$UBI_i = \frac{E_{upgrade}\left[SSI\right] - E\left[SSI\right]}{1 - E\left[SSI\right]} \tag{5.12}$$

in which $E_{upgrade}[SSI]$ is the expected value of *SSI* given that the *i*-th pipe is "upgraded." By "upgrade", it is meant that the probability of pipe damage given an earthquake is significantly smaller than its value before upgrade. UBI_i is the percent increase of SSI given that the *i*-th pipe is upgraded, and its relative value is a measure of the pipe impact on the overall system serviceability.

- **Voltage Ratio**, or VR [Level II]

For each bus inside the substations, this index is defined as the ratio of the voltage magnitude in the seismically damaged network ($V_{i,s}$) to the reference value for non-seismic, normal conditions $V_{i,0}$:

$$VR_i = V_{i,s} / V_{i,0} \tag{5.13}$$

The voltage computation requires a power-flow analysis on the network. Hence this index expresses a functional consequence in the i-th component of the physical damage to all system components. When interactions with other systems are modelled, VR_i expresses the functional consequence in the i-th component of the physical damage to components of all the interacting systems, i.e. it is the value of the index that changes due to the inter- and intra-dependencies, not its definition.

System-Level Performance Indicators (PIs)

- **Simple Connectivity Loss** or SCL [Level I] (Poljanšek et al. 2012)

Same as for GAS (Sect. 5.3.2.8),
Connectivity loss (CL) measures the average reduction in the ability of sinks (e.g. load buses) to receive flow from sources (power plants) by counting the number of the sources connected to the i-th sink in the original (undamaged) network $N^i_{source,orig}$ and then in the damaged network $N^i_{source,dam}$.

$$CL = 1 - \left\langle \frac{N^i_{source,dam}}{N^i_{source,orig}} \right\rangle_i \tag{5.14}$$

- **System Serviceability Index**, or SSI [Level II]

The System Serviceability Index can be defined for EPN as in Vanzi (1995), by the ratio of the sum of the real power delivered from load buses after an earthquake, to that before the earthquake:

$$SSI = \frac{\sum_{i=1}^{N_D} P_{i,0}\,(1 - R_i)\,w_i}{\sum_{i=1}^{N_D} P_{i,0}} \tag{5.15}$$

Where $P_{i,0}$ is the real power delivered from the i-th load bus in non-seismic condition. In order to compute the eventually reduced power delivered in seismic conditions, two factors are considered. The first one, $R_i = \frac{|V_{i,s} - V_{i,0}|}{V_{i,0}}$, with $V_{i,s}$ and $V_{i,0}$ the voltage magnitudes in seismic and non-seismic conditions, is the percent reduction of voltage in the i-th load bus and if $Vi,s < Vi$, one has $1 - R_i = VR_i$ The second factor, w_i, is a weight function accounting for the small tolerance on voltage reduction: in particular, its value is 1 for $R_i < 10\ \%$ and 0 otherwise. The *SSI* index varies between 0 and 1, assuming the value 0 when there is no solution for the power-flow analysis and 1 when the EPN remains undamaged after the earthquake.

The above definition assumes that the demand remains fixed before and after the earthquake, since the index looks only at a single system, without considering the interactions of the EPN with the other infrastructure systems. It can be improved upon and redefined as the *ESSI* that follows.

- **Enhanced System Serviceability Index**, or ESSI [Level II]

The Enhanced System Serviceability Index is an enhancement of the *SSI*, defined to capture the interaction of the EPN with the built area of the study region. In order to model this interaction, the power demand is eventually reduced of the fraction corresponding to collapsed buildings. The *ESSI* is defined as:

$$ESSI = \frac{\sum_{i=1}^{N_D} P_{i,0}\,(1 - R_i)\, w_i \frac{\sum_{j\in I_i} N_{j,\overline{CO}}}{\sum_{j\in I_i} N_j}}{\sum_{i=1}^{N_D} P_{i,0} \frac{\sum_{j\in I_i} N_{j,\overline{CO}}}{\sum_{j\in I_i} N_j}} \tag{5.16}$$

where I_i is the set of tributary cells for the i-th load bus, N_j is the total number of buildings inside the *j*-th tributary cell and $N_{j,\overline{CO}}$ is the number of not collapsed buildings inside the *j*-th tributary cell. As the *SSI*, the *ESSI* index also varies between 0 and 1, assuming the value 0 when there is no solution for the power-flow analysis or all buildings in the study region are collapsed and 1 when the EPN remains undamaged after the earthquake.

5.3.2.13 Transportation Networks

This chapter concerns mostly the road system. The railway system will be introduced, but no details will be provided. The damage to the network causes traffic congestion, resulting in increased travel time, which is in turn translated into monetary terms.

Structure of the System and Input Attributes

The Road Network is a directed graph composed of a number of nodes and edges.. In a directed graph, one-way edges are usually referred to as arcs and a two-way edge can then be virtually decomposed in two arcs (one for each opposite direction).

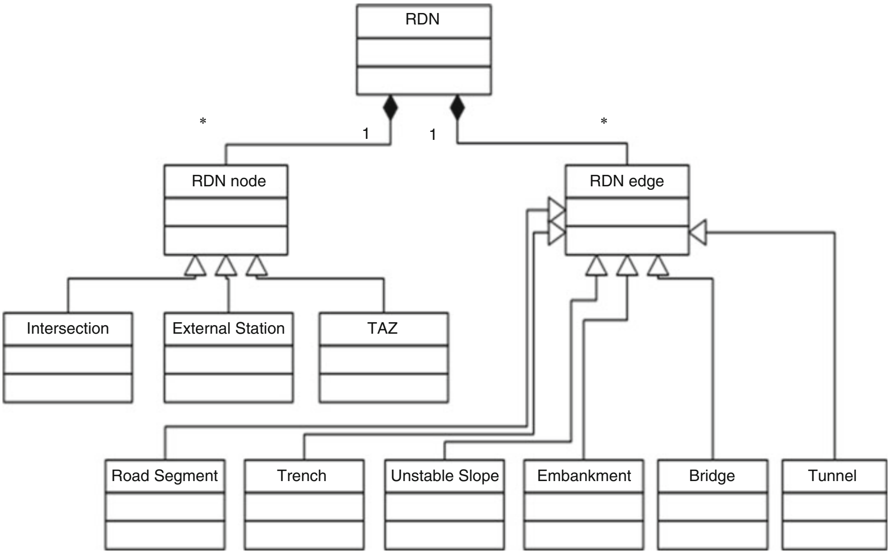

Fig. 5.5 UML class-diagram of the Road Transportation Network (RDN)

All edges are in general vulnerable to seismic shaking or geotechnical hazards (i.e., ground failure due to liquefaction, landslides and fault rupture). Some types of edges or road segments, like those identified below, have specific types of response to seismic action and associated vulnerability (Fig. 5.5 and Table 5.10).

The identified system components are:

RDN01:	Bridge	[Points or edges]
RDN02:	Tunnel	[Edges]
RDN03:	Embankment (road on)	[Edges]
RDN04:	Trench (road in a)	[Edges]
RDN05:	Unstable slope (road on, or running along)	[Edges]
RDN06:	Road pavements	[Edges]
RDN07:	Bridges abutments	[Points or edges]

The Railway system as a whole is composed of a number of point-like critical facilities (Stations) and of the Railway Network itself. The internal logic of the stations and their function in the traffic management of the whole system should be modelled explicitly. The network portion of the system has the same components as a Road network, plus a supervisory control and data acquisition – SCADA – subsystem. The difference is in the fragility models as the railway tracks present lower tolerance to damage compared to roadways.

Table 5.10 Main attributes/properties of the Road Transportation Network class

Group	Attribute(s)	Description
Global properties	tripDemand	Origin-destination matrix built from the TAZ nodes
	roadBlockageModel	Road blockage model to be used
	roadBlockageCoefficients	Coefficients of road blockage model to be used
Pointers	road, trench, embank, unstSlope, tunnel, bridge	Pointers to all road pavements, trenches, embankments, unstable slopes, tunnels, bridges, which are assigned specific fragility functions
	intersection	Pointers to all intersections, objects from the Intersection class
	external	Pointers to all external stations, objects from the ExternalStation class
	taz	Pointers to all Traffic Analysis Zones, objects from the TAZ class
Edge properties stored at RDN level	speed, lanes, dependency, hierarchy	Length, centroid, etc. are attributes inherited from the Directed Network class. Here the network-specific properties are listed (free-flow speed, number of lanes, classification, etc.)
Node properties stored at RDN level	tazType	Type of Traffic Analysis Zones (type of trip demand)
State variables recording RDN state	states	$n_E \times 1$ collection of properties that describe the current state for each of the n_E events (fields: damage state, isBroken, isBlocked, SCL, WCL, isolatedTAZ, etc.)

The identified system components are:

RWN01:	Bridge, same as per RDN	[Points or edges]
RWN02:	Tunnel, same as per RDN	[Edges]
RWN03:	Embankment (road on), same as per RDN	[Edges]
RWN04:	Trench (road in a), same as per RDN	[Edges]
RWN05:	Unstable slope, same as per RDN	[Edges]
RWN06:	Tracks	[Edges]
RWN07:	Bridges abutments	[Points or edges]
RWN08:	Station	[Points]

5.3.2.14 Interdependencies

Road transportation networks play a central part in the analysis of the system of systems, as they must connect all the strategic facilities and the inhabited areas.

- **BDG ➔ RDN [Geographical]:**
  In a urban setting, structural damage to buildings produces debris that can cause road blockages.
- **HBR ➔ RDN [Demand]:**
  Demand for transportation (which concur to the determination of the origin-destination matrix that drives traffic flows) of goods is generated in HBR (HBR is an origin).
- **HCS ➔ RDN [Demand]:**
  Demand for transportation is generated in HCS (as origins for ambulances searching for victims and destination for returning ambulances).
- **RDN ➔ BDG [Physical]:**
  Damage to the transportation network can block access to damaged buildings hindering emergency response.
- **RDN ➔ HBR [Physical]:**
  Damage to the transportation network can block access to the HBR preventing goods to be dispatched and causing large economic loss.
- **RDN ➔ HCS [Physical]:**
  Damage to the transportation network can block access to health-care facilities hindering emergency response.
- **WSS ➔ RDN [Geographical]:**
  Damage and leakage of water pipes underneath the roadways can cause disruption of traffic.

5.3.2.15 Methods for Systemic Analysis

The selected works referenced in this section can be classified according to the level of analysis of the functionality of the transportation network. In a way of classification, available studies can be assigned to the following three levels:

- **Level 0 (Vulnerability analysis):**
  - Level 0 analysis is a basic vulnerability analysis and it is related to the physical performance of a single component of the network (e.g. damages to roads, tunnel or bridges
- **Level I (Connectivity analysis):**
  - Level I analyses are studying the integrity of the network in terms of pure connectivity focussing on the services provided by the network, most typically the rescue function immediately after the earthquake. They may be of interest in identifying portions of the network that are critical to keep the connectivity between most of the points of the networks.
  - Two similar examples of Level I studies can be found in Franchin et al. (2006) and in Nuti and Vanzi (1998). In the latter study the road network serves the purpose of connecting the hospitals to a regional health-care system. A further

example of Level I study is given by Kang et al. (2008). The authors apply a matrix-based system reliability (MSR) method to a transportation network where bridge structures are considered as vulnerable, in order to evaluate the probability of disconnection between each city/county and a critical facility.

- **Level IIa (Capacity analysis):**
  - The scope of the Capacity analysis is widened to include consideration of the network capacity to accommodate traffic flows.
  - Examples of Level II studies are those in Shinozuka et al. (2003) and Chang et al. (2011). The approach in Shinozuka et al. (2003) aims at determining the direct and indirect economic loss due to damage to a transportation network. Direct loss is related to physical damage to vulnerable components, while indirect loss is related to functionality of the transportation system, whose degradation is measured in terms of a system-level performance index called Driver's delay (DD), i.e., the increase in total daily travel time for all travellers. This study is extended in Zhou et al. (2004), to consider the effect of retrofit strategies in improving the performance in future events. The work by Chang et al. (2011) advances a proposal for going beyond the use of the pre-earthquake (static) origin-destination matrix as an input for traffic flow analysis. The post-quake travel demand is complicated and the change of traffic pattern after the event is coupled with the damage of transportation infrastructures.

- **Level IIb (Serviceability analysis):**
  - This more general approach aims at obtaining a realistic estimate of total loss, inclusive of direct physical damage to the built environment (residential and industrial buildings as well as network components), loss due to reduced activity in the economic sectors (industry, services), and losses due to (increased travel time). Economic interdependencies are accounted for, such as the reduction in demand and supply of commodities (due to damaged factories, etc.), hence in the demand for travel, and due to the increased travel costs. At this level the relevance and the complexity of the economic models become dominant over that of the transportation network. This is a full systemic study requiring important inputs from the economic disciplines.
  - Among the few available Level IIb studies, an example is the work by Karaca (2005). The work reports a regional earthquake loss methodology that emphasizes economic interdependencies at regional and national scales and the mediating role of the transportation network. The effectiveness of alternative mitigation strategies is also considered. The loss assessment methodology includes spatial interactions (through the transportation network) and business interaction (through an input-output model). The losses reflect damage to buildings and transportation components, reduced functionality, changes in the level of economic activity in different economic sectors and geographical regions, and the speed of the reconstruction/recovery process.

Table 5.11 Most relevant UML-methods of the Road Transportation Network class

Method	Description
evaluateRDNdamage	Evaluates the damage state of each component
addSecondEdge	Adds a second edge in the model from end to start node, if a two-way travel is requested
discretizeEdges	Subdivides all the links with a length greater than a threshold into smaller segments
updateConnectivity	Sets to 0 the elements in the adjacency matrix corresponding to broken edges and checks if TAZ's are isolated from each other
setRoadBlockageModel	Computes and Samples the road blockage probability based on the collapsed buildings in each cell
computePerformanceIndicator	Computes the different PIs at component- and system-level

The connectivity approach used in the SYNER-G framework uses the set of UML-methods presented in Table 5.11 and is applied to a road network in Italy (Chap. 10).

5.3.2.16 Performance Indicators

Performance indicators are defined to estimate the performance of the Road Network at component or system-level, for the aforementioned different level of analysis.

Component-Level Performance Indicators (PIs)

- *Nodes:* **Connectivity reliability *[Level I]***

Connectivity reliability estimates the probability that the network nodes remain connected. A special case of connectivity reliability is the terminal reliability (Iida and Wakabayashi 1989), which concerns the existence of a path between a specific origin-destination (OD) pair. For each node, the network is considered successful if at least one path is operational. A path consists of a set of components (roadways, also called arcs), which are characterized by a binary variable denoting their state (operating or failed). Capacity constraints on the arcs are not accounted for.

- *Nodes:* **Travel time reliability *[Level IIa]***

This indicator is defined as the probability that a trip between a given OD pair can be made successful within a specified interval of time (Asakura and Kashiwadani 1991). This measure is useful to evaluate network performances under both normal daily flow variations and seismic conditions. Let C and C_0 be the vectors of damaged and undamaged states of the arcs along the paths and the corresponding travel times between the OD pair w in these two states be denoted as $t_w(C)$ and $t_w(C_0)$.

The travel time reliability is the defined as the probability $\tau_w(\theta)$ of the ratio of $t_w(C)$ to $t_w(C_0)$ being lower than an acceptable level θ.

$$\tau_w(\theta) = P\left(\frac{t_w(C)}{t_w(C_0)} \leq \theta\right) \tag{5.17}$$

The value θ can be interpreted as the level of service that should be maintained despite the capacity reduction that has occurred on some arcs in the network. This index expresses a functional consequence for OD pair of the physical damage to $\tau_w(\theta)$ expresses the functional consequence for OD pair of the physical damage to components of all the interacting systems, i.e. it is the value of the index that changes due to the inter-and intra-dependencies, not its definition.

- *Nodes:* **Minimum travel time** ***[Level II or III]***

It is the time needed to reach a critical facility, for example a hospital, computed for each TAZ centroid.

System-Level Performance Indicators (PIs)

- **Simple Connectivity Loss**, or SCL. ***[Level I]***

This definition of this index is based on the concept of connectivity (Poljanšek et al. 2012); for a generic system it measures the average reduction in the ability of sink nodes (i.e. destination points in this case) to receive flow from source nodes (i.e. origin nodes in this case):

$$SCL = 1 - \left\langle \frac{N_s^i}{N_0^i} \right\rangle_i \tag{5.18}$$

Where < > denotes averaging over all sink vertices, while N_s^i and N_0^i are the number of sources connected to the *i*-th sink in the seismically damaged network and in non-seismic conditions, respectively. With reference to a RDN, all the single TAZ's, taken one at a time, are considered sinks, whereas all the remaining TAZ's are sources.

- **Weighted Connectivity Loss**, or WCL. ***[Level I]***

This index upgrades the simple connectivity loss by weighting the number of sources (i.e. origin point) connected to the *i*-th sink (i.e. destination point), in the seismically damaged network and in non-seismic conditions, respectively:

$$WCL = 1 - \left\langle \frac{N_s^i W_s^i}{N_0^i W_0^i} \right\rangle_i \tag{5.19}$$

Where the weights W_s^i and W_0^i can be defined in different ways. The authors here defined them as the sum of the inverse of the number of edges composing the single paths between the *i*-th sink and the sources, in the seismically damaged network and in non-seismic conditions, respectively:

$$W^i = \sum_{j,j \neq i} I_{ij} \frac{1}{TT_{ij}} \tag{5.20}$$

where I_{ij} is the indicator function (indicating the existence of a path between the *i*-th sink and the j-th source, TT_{ij} is the travel time of the path between the *i*-th sink and the *j*-th source and *j* spans all the source nodes, i.e. all TAZ's excluded the *i*-th one.

- **Driver's delay**, or DD. ***[Level IIa]***

This system-level performance index one of the most classical (Shinozuka et al. 2003); it is defined as the increase in total daily travel time (hours/day) for all travellers, not distinguishing between commuters and commercial vehicles:

$$DD = \sum_a x'_a t'_a\left(x'_a\right) - \sum_a x_a t_a\left(x_a\right) \tag{5.21}$$

Where x_a and x'_a denote the traffic flows (in PCU[2]/day) on the *a*-th link in the prevent undamaged and the damaged conditions, respectively, while $t_a(x_a)$ and $t'_a(x'_a)$ denote the corresponding travel times (hours/PCU), which depend on the congestion level through the model:

$$t_a = t_a^0\left[1 + \alpha\left(\frac{x_a}{c_a}\right)^\beta\right] \tag{5.22}$$

Where c_a is the practical capacity of the link (in PCU/day), t_a^0 the travel time at "zero" flow in the link, α and β are model parameters (frequently assigned values for α and β are 0.15 and 4.0, respectively).

- **Capacity reliability** ***[Level IIb]***

This quantity is defined as the probability that the network can accommodate a certain traffic demand at a required service level, while accounting for drivers' route choice behaviour (Chen et al. 1999). Travel time reliability can also be obtained as a side product. This measure provides important information for efficient flow control, capacity expansion and other relevant works to enhance the reliability of a road network. The maximum capacity of the network, μ, can be computed from the capacities of all the arcs:

$$\mu = g\left(c_1, c_2, \ldots., c_a\right) \tag{5.23}$$

[2]Passenger Car Unit.

Let μ_r denote a required demand level the capacity reliability is given as the probability of μ exceeding μ_r:

$$R(\mu_r) = P(\mu \geq \mu_r) \tag{5.24}$$

This probability predicts how reliably the existing network with damaged arcs can accommodate a given level of required demand. It is easy to see that the boundary conditions must satisfy the following cases:

$$-R(\mu_r = 0) = 1 \tag{5.25}$$

$$-R(\mu_r = \infty) = 0 \tag{5.26}$$

It should be noted that connectivity reliability (level I) is actually a specific case of capacity reliability (level III), where only binary damage states are used and the arcs are either functional or not (i.e. no capacity constraint).

- **Overall travel time reliability *[Level IIb]***

  It is sometimes more convenient to use a single index to describe the overall performance of the system and this OD travel time reliability satisfies this need for a reliability measure of the whole road network (Chen et al 2002). However, it is difficult to define such an index because of the interdependence of the individual OD travel times. In the literature, three possible indices representing the overall travel time reliability of the system are provided:

$$\tau_{\min}(\theta) = \min_w \{\tau_w(\theta)\} \tag{5.27}$$

$$\tau_{avg}(\theta) = \frac{1}{W}\sum_{w=1}^{W} \tau_w(\theta) \tag{5.28}$$

$$\tau_{wgt}(\theta) = \frac{\sum_{w=1}^{W} \tau_w(\theta)\, q_w}{\sum_{w=1}^{W} q_w} \tag{5.29}$$

$\tau_{min}(\theta)$ takes the minimum of all OD travel time reliabilities as the overall travel time reliability for a given level of service θ . It is a conservative measure and may not truly reflect the performance of the system. $\tau_{avg}(\theta)$ is a simple arithmetic average of all OD travel time reliabilities and $\tau_{wgt}(\theta)$ is a weighted average of all OD travel time reliabilities by weighing the contribution of each OD pair by its travel demand q_w.

5.3.3 Critical Facilities

In SYNER-G, only two critical facilities are considered: harbours and health-care facilities. They are two examples on how critical facilities can be integrated in the global assessment of a system of systems, and play important roles in society in normal times, and an even exacerbated role during crisis.

5.3.3.1 Harbour System

Port transportation systems are critical facilities whose function is to transport cargos and people. They contain a wide variety of facilities for passenger operations and transport, cargo handling and storage, rail and road transport of facility users and cargoes, communication, guidance, maintenance, administration, utilities, and various supporting operations. Ports offer wide-open areas that can be used for emergency or refuge activities after a damaging earthquake. Moreover, ports can play an important role during the recovery period, as they contribute to the reconstruction assistance and the transportation of goods for homeless citizens.

Harbours are part of the general transportation system, often either as an entrance or an exit to close continental, terrestrial systems.

Structure of the System

Harbours are complex systems comprising all the activities related to the transfer of goods/passengers between the maritime transportation and the earth-bound transportation systems. Often they have important storage facilities as well (oil reservoirs, tanks, silos, etc.). They are serviced by a number of other systems including: EPN, WSS, WWN, FFS, GAS, RDN, RWN. The identified system components are:

- *HBR01:* Waterfront components (wharves, breakwaters, etc.)
- *HBR02:* Earthen embankments (backfills, some time hydraulic fills, and native soil material)
- *HBR03:* Cargo handling and storage components (cranes, tanks, etc.)
- *HBR04:* Buildings (sheds, warehouse, offices, control towers etc.)
- *HBR05:* Liquid fuel system (components as per the OIL system)

Also almost all other utility and transportation systems are present within port facilities, like water and waste-water systems, electric power networks, gas supplying systems, road and railway networks. The ports' functionality is dependent on the functioning of each system/component, taking also into consideration the interactions between them.

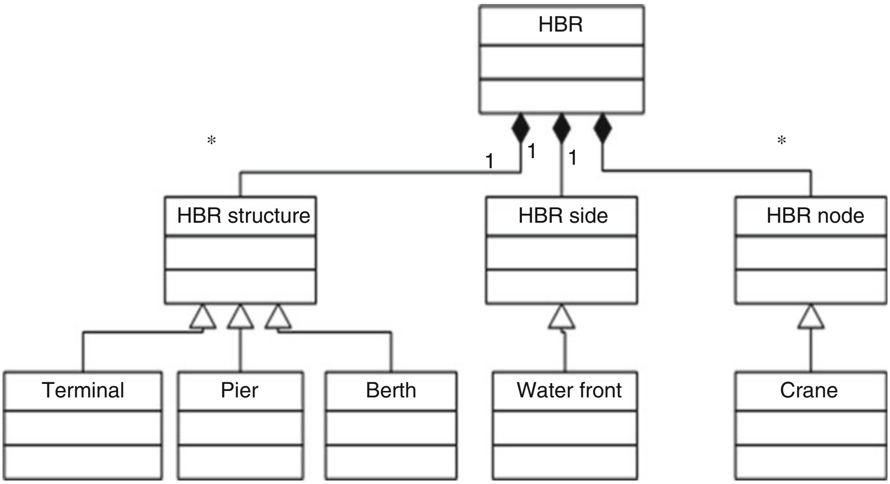

Fig. 5.6 UML class-diagram of the Harbour System (HBR)

Table 5.12 Main attributes/properties of the Harbour System class according to SYNER-G

Group	Attribute	Description
Geometry	nodePosition	Coordinates of the component vertices
Physical damageability	vulnSites	List of vulnerable sites of the HBR, containing their location and IM types
	isVulnerable	Boolean variable determining whether or not the physical damage of the component has to be computed
	typeFragility	Fragility model to be assigned to each of the vulnerablecomponents
System functionality	typeFunctionality	Functionality model, relating physical damages to functional damages, for each vulnerable component
	crane, waterfront, berth, pier, terminal	Pointers to all the cranes, waterfronts, berths, piers and terminals in the system
Interdependence modeling	EPNlinks, RDNlinks	Pointers to the EPN and RDN links connecting the different HBR components
State variables recording system/component state	states	$n_E \times 1$ collection of properties that describe the current state for each of the n_E events (fields: damage state, isolated EPN and RDN nodes, TCoH, TCoM, etc.)

The objet-oriented structure of the Harbour System as defined in SYNER-G as well as the main attributes of the class are presented in Fig. 5.6 and Table 5.12. An illustration of potential applications is described for the Thessaloniki harbor in Chap. 12 of this book.

5.3.3.2 Interdependencies

As Harbours are critical facilities composed of the different systems considered in SYNER-G, interdependencies exist with all the systems. However the main ones are the following ones:

- **EPN ➔HBR [Physical]:**
  Damage to the EPN can prevent functioning of critical components in the HBR system (e.g., cargo handling equipment).
- **RDN ➔ HBR [Physical]:**
  Damage to the transportation network can block access to the HBR preventing goods to be dispatched and causing large economic loss.
- **HBR ➔ RDN [Demand]:**
  Demand for transportation (which concur to the determination of the origin-destination matrix that drives traffic flows) of goods is generated in HBR (HBR is an origin).

5.3.3.3 Methods for Systemic Analysis

Current engineering practice for seismic risk reduction of port facilities is typically based on design or retrofit criteria for individual physical components (e.g. wharf structures) expressed as prescribed levels of displacement, strain, etc. However, the resilience and continuity of shipping operations at a port after an earthquake depend not only on the performance of these individual components, but on their locations, redundancy, and physical and operational connectivity to utility networks as well; that is, on the port system as a whole.

- **Level 0 (Vulnerability analysis)**
  - In most of the post-seismic studies, the performances of the harbours are analysed regarding the physical integrity of the different elements constituting the port systems. The loss of functionality and the recovery are only seldom considered.
  - Hence, almost all the available literature on seismic risk evaluation for port systems focus on the direct physical damages, sometimes with the estimation of the associated cost (NIBS 2004). Shinozuka (2009) developed a model to estimate the physical vulnerability of harbour systems to earthquakes, and the corresponding uncertainties using fragility curves.
  - The economic consequences, caused by losses of incomes, interruption of business or other induced effects for other economic sectors, are estimated only in few studies (Pachakis and Kiremidjian 2003, 2004; Na et al. 2007, 2008).
- **Level II (Capacity analysis)**
  - The integration of indirect costs and functionality losses in seismic risk evaluation is more recent.

Table 5.13 Most relevant UML-methods of the Harbour System class

Method	Description
evaluateHBRdamage	Evaluates the damage state of each Harbour component
evaluateHBRfunctionality	Evaluates the functionality of each Harbour component
retrieveEPNandRDNstates	Checks the state of the EPN and RDN components to ensure the functionality of the Harbour components
computePerformanceIndicator	Computes the different PIs at component- and system-level

– Combining a model estimating the physical damages with a model to estimate losses of revenues caused by the induced closure of the ports, Pachakis and Kiremidjian (2003, 2004) developed a methodology to simulate the response of a harbour system to earthquakes. Two classes of losses are defined: direct losses due to physical damages and indirect losses caused by the modification of conditions of operability of the port systems. Hence, the methodology simulates physical damages, but also takes into account planning and management of the risk. More recent studies also estimate the seismic risk of harbours through the evaluations of both physical damages and revenue losses (Na et al. 2007, 2008; Na and Shinozuka 2009).

The main UML-methods used in the SYNER-G approach to analyse the Harbour System are described in Table 5.13.

5.3.3.4 Performance Indicators

Performance indicators of harbours can be estimated in terms of either quantities of inputs handled or number of boats taken care of.

Container terminals:

- *Terminal:* **Total number of containers handled or** TCoH
  TCoH = total number of containers handled (loaded and unloaded) per day, in Twentyfoot Equivalent Units (TEU)[3]
- *Gate:* **Total number of containers' movements or** TCoM
  TCoM = total number of containers' movements per day, in Twenty-foot Equivalent Units (TEU) (in the whole harbor facility)

Bulk cargo terminals:

- *Terminal:* **Total cargo handled** or TCaH
  TCaH = total cargo handled (loaded and unloaded) per day, in tones
- *Gate:* **Total cargo movements** or TCaM
  TCoM = total cargo movements per DAY, in tones (in the whole harbor facility)

[3]TEU is not a standardized unit. It corresponds to the volume of a 20-foot-long (6.1m) intermodal container, and is often used to estimate the capacity of transportation systems (e.g. boats or terminals).

5.3.3.5 Health-Care System

Hospital facilities are critical infrastructures of the health-care systems From an engineering point of view these systems are made of many components of different types that jointly contribute to provide an output, which are the medical services in the case of hospital. From a social point of view, hospitals provide a fundamental assistance to citizens in every-day life and their function becomes of paramount importance in the case of a disaster. Therefore they are classified as critical facilities.

Structure of the System

The health-care system is made up of health-care facilities (HCF): hospitals, clinics, and all buildings providing medical cares. Hospitals are systems whose function is delivering medical services, which consist of standardized procedures to guarantee an adequate treatment of patients. These procedures are delivered to patients by a joint contribution of the three "active" components of the system:

- The *operators* (human component) namely medical personnel, doctors, nurses and in general whoever plays an active role in providing medical care;
- The *facility* (physical component) i.e. buildings and other sub-components and facilities where medical services are delivered;
- The *organization* (organizational component), which consists of the hospital management, responsible of setting up adequate conditions (standardized procedures for ordinary and emergency conditions) so that the medical services can be delivered.

The identified system components are:

- *HCS01:* Organizational component
- *HCS02:* Human component
- *HCS03:* Physical Component
  - *HCS03-1:* Structural elements (of the buildings within the complex/facility)
  - *HCS03-2:* Non-structural elements/Architectural
  - *HCS03-3:* Non-structural elements/Basic installations/Medical gases
  - *HCS03-4:* Non-structural elements/Basic installations/Power system
  - *HCS03-5:* Non-structural elements/Basic installations/Water system
  - *HCS03-6:* Non-structural elements/Basic installations/Conveying system
  - *HCS03-7:* Non-structural elements/Content-Equipment

The structure of the Health-Care System and the corresponding attributes are detailed in Fig. 5.7 and Table 5.14.

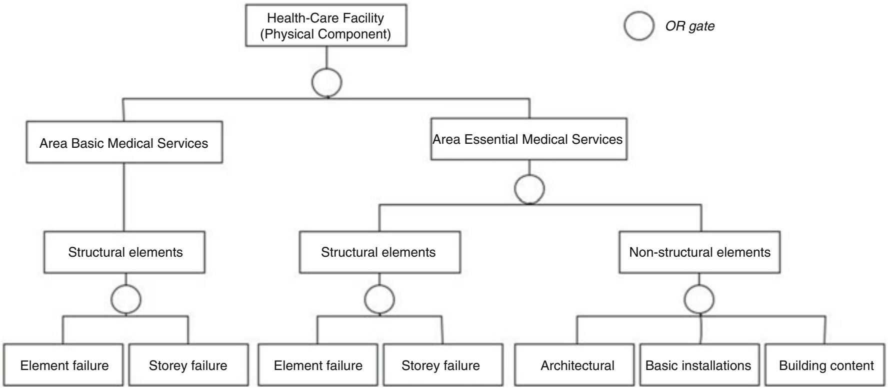

Fig. 5.7 Fault-tree structure of the physical component of the Health-Care System with a description of the main sub-components

Table 5.14 Main attributes/properties of the Health-Care System class

Group	Attribute	Description
Geometry	nodePosition	Coordinates of the network vertices (i.e. health-care centers)
	connectivity	Connectivity matrix listing the start and end nodes of each RDN link
System Functionality	HTC	Health-care facility's treatment capacity
Interdependence modeling	accessibility	Accessibility to the health-care facilities through the rod network
	utilityLoss	Level of service in basic utilities for the health-care facilities
State variables recording system/component state	states	$n_E \times 1$ collection of properties that describe the current state for each of the n_E events (fields: damage state, isolated health-care facilities, HTC, Nb of available operating theatres, Nb of beds, etc.)

5.3.3.6 Interdependencies

Health-care facilities form "high-end" systems, in the sense that they are located at downstream of the global system, needing inputs from almost all other systems to operate.

- **BDG ➔ HCS [Demand]:**
  Structural and non-structural damage to buildings may result in casualties that need to be treated in a health-care facility and hence determine the demand on this system.
- **EPN➔ HCS [Physical]:**
  Damage to the EPN can prevent power to be fed to the health-care facilities hindering emergency response in case a joint failure of backup power sources occur.

- **WSS➔ HCS [Physical]:**
  Damage to the WSS can prevent water to be delivered to the health-care facilities hindering emergency response over time in case backup reservoirs are depleted.
- **GAS➔ HCS [Physical]:**
  Damage to the GAS system can prevent natural gas to be fed to the health-care facilities hindering emergency response in case backup power sources depend on gas fuel.
- **RDN➔ HCS [Physical]:**
  Damage to the transportation network can block access to damaged buildings hindering emergency response.
- **HCS ➔ RDN [Demand]:**
  Demand for transportation is generated in HCS (as a destination).

5.3.3.7 Methods for Systemic Analysis

The health-care system is made up of health-care facilities, collectively serving a region, city or part of a city and coping with the earthquake induced surge in treatment demand in the aftermath of an event. Notwithstanding the criticality of the function of the HCS, the technical literature on the matter is all but abundant. Few studies can be found, some with a focus on the assessment of the capacity of a single facility to remain operational, even if partially, under emergency conditions with possible damage to the facility structural and non-structural components. The remaining few studies deal with the entire system at the regional level and try to evaluate so-called community impact.

For instance, in Monti and Nuti (1996) a reliability-based (FORM, SORM and bounds) procedure to evaluate the functional vulnerability of the surgical function of a hospital system is presented. In Nuti and Vanzi (1998) the regional system of hospitals is studied with the aim of setting up a model for their availability. Such a model is proposed to assess the best retrofit strategies from a systemic point of view, as well as emergency measures such as the use of camp hospitals. Another study which deals with the system as a collection of facilities is Menoni et al. (2002), where the capacity of public facilities can continue providing their service under stressful conditions, even when a certain degree of physical damage has been suffered by structures or by medical equipment, is investigated.

Recent studies try to look at the resilience of the hospital system, as in Cimellaro et al. (2010, 2011). The latter introduces an organizational model, a metamodel, describing the response of the Hospital Emergency Department (ED), which is able to estimate the hospital capacity and the dynamic response in real time and to incorporate the influence of the damage of structural and non-structural components on the organizational ones. The performance indicator chosen to assess the structure is the waiting time. The metamodel covers a large range of hospital configurations and takes into account hospital resources, in terms of staff and infrastructures, operational efficiency and existence of an emergency plan, maximum capacity and behaviour both in saturated and over-capacitated conditions.

Table 5.15 Most relevant UML-methods of the Health-Care System class

UML-Method	Description
evaluateHCSdamage	Evaluates the physical damage state of each health-care center
evaluateHTC	Evaluate the Hospital Treatment Capacity of each health-care center
evaluateHCSaccessibility	Evaluates the accessibility of each health-care center based on the functional state of the road network
performCasualtiesTransportation	Assign each casualty to a health-care center based on the HTC and the accessibility, through an iterative algorithm
computePerformanceIndicator	Computes the different PIs at component- and system-level

Similarly, in Lupoi et al. (2008), a methodology is given to compare treatment demand and capacity for a facility under emergency conditions. Performance is measured in terms of the mean annual rate of demand exceeding a random treatment capacity:

The capacity is measured in terms of number of surgical operations that can be carried out per hour. The demand is evaluated starting from the total number of casualties and using severity classes to find the subset of those requiring surgical treatment.

The capacity term is the result of three contributions, coming from the three macro-components (m/c) making up the hospital system: the physical m/c (structural and non-structural element of the facility), the organizational m/c (the procedure in the emergency plans) and the human m/c (skill and training of the operators using the facilities and equipment according to the procedures).

Some of the UML-methods used is the SYNER-G approach are presented in Table 5.15.

5.3.3.8 Performance Indicators

System-Level Performance Indicators (PIs)

- **Hospital Treatment Capacity**, or HTC

This system-level index expresses the number of patients that can be given surgical treatment per hour (Lupoi et al. 2008). It is defined as:

$$HTC = \frac{\alpha \cdot \beta \cdot \gamma_1 \gamma_2}{t_m} \tag{5.30}$$

where α and β are factors accounting for organizational and human macro-components of the hospital system, γ_1 is the number of undamaged operating theatres, γ_2 a Boolean variable that takes upon the value of one when essential utilities needed for the functioning of the operating theatres are properly working, zero otherwise, and t_m is the average duration of surgical treatment. The performance of the system relative to its pre-earthquake state can be measured through HTC either by taking its ratio to the pre-earthquake value $HTCR = HTC/HTC_0$, or by taking its ratio to the corresponding demand HTC/HTD.[4]

5.4 Synthesis

The several systems that have been described in this chapter are summarized in Table 5.16, where the analysis levels and corresponding performance indicators are outlined.

Table 5.16 Summary of the possible analysis levels and performance indicators for each of the systems studied within the SYNER-G project

System	Analysis levels	Main performance indicators
Buildings	+ Level 0 (vulnerability analysis): + Level II (serviceability)	**Component level** *Building:* **Building damage *[Level 0]*** *Building:* **Building usability *[Level 0]*** *Building:* **Casualties *[Level 0]*** *Building:* **Building habitability *[Level II]*** **System level** **Repartition of Building damages *[Level 0]*** **Repartition of Building usability *[Level 0]*** **Repartition of Casualties *[Level 0]*** **Repartition of Building habitability *[Level II]***
Electric power	+ Level 0 (vulnerability analysis): + Level I (connectivity analysis) + Level II (capacity analysis)	**Component level** *Lines/Nodes:* **Damage Consequence Index**, or DCI. ***[Level II]*** (Wang et al. 2010) *Lines/nodes:* **Upgrade Benefit Index**, or UBI. ***[Level II]*** (Wang et al 2010) *Substations:* **Voltage Ratio**, or VR ***[Level II]*** **System level** **Average Head Ratio**, or AHR. ***[Level II]*** **Simple Connectivity Loss** or SCL ***[Level I]*** (Poljanšek et al. 2012) **System Serviceability Index**, or SSI ***[Level II]*** **Enhanced System Serviceability Index**, or ESSI ***[Level II]***

(continued)

[4]HTD = Hospital Treatment Demand.

Table 5.16 (continued)

System	Analysis levels	Main performance indicators
Water supply and waste-water	+ Level 0 (vulnerability analysis): + Level I (connectivity analysis) + Level II (flow analysis/ serviceability analysis)	**Component level** *Junctions/Nodes:* **Head Ratio**, or HR. ***[Level II]*** *Pipes:* the **Damage Consequence Index**, or DCI. ***[Level II]*** (Wang et al 2010) *Pipes:* **Upgrade Benefit Index**, or UBI. ***[Level II]*** (Wang et al. 2010) **System level** **Average Head Ratio**, or AHR. ***[Level II]*** **System Serviceability Index**, or SSI. ***[Level II]*** (Wang et al. 2010).
Gas and oil	+ Level 0 (vulnerability analysis): + Level I (connectivity analysis) + Level II (flow-performance reliability analysis)	**Component level** *Demand Nodes*: **Customer Connectivity** or CC. ***[Level I]*** *Pipelines:* **Damage Consequence Index** or DCI. ***[Level II]*** (Wang et al. 2010) *Nodes*: **Pressure Ratio** or PR. ***[Level II]*** **System level** **Utility customer density.** ***[Level I]*** **System Serviceability Index** or SSI. ***[Level II]*** (Wang et al. 2010) **Connectivity Loss** or CL. ***[Level I]*** (Poljanšek et al. 2012) **Serviceability ratio** or S. ***[Level II]*** (Adachi and Ellingwood 2008) **Average Pressure Ratio** or APR. ***[Level II]***
Road transportation	+ Level 0 (vulnerability analysis): + Level I (connectivity analysis) + Level IIa (capacity analysis) + Level IIb (serviceability analysis)	**Component level** *Nodes:* **Connectivity reliability** ***[Level I]*** *Nodes:* **Travel time reliability** ***[Level II]*** (Asakura and Kashiwadani 1991) *Nodes:* **Minimum travel time** [***Level IIa or IIb]*** **System level** **Simple Connectivity Loss**, or SCL. ***[Level I]*** (Poljanšek et al. 2012) **Weighted Connectivity Loss**, or WCL. ***[Level I]*** **Driver's delay**, or DD. ***[Level IIa]*** (Shinozuka et al. 2003) **Capacity reliability** ***[Level IIb]*** (Chen et al. 1999) **Overall travel time reliability** ***[Level IIb]*** (Chen et al. 2002) **Capacity reliability** ***[Level IIb]*** (Chen et al. 1999) **Overall travel time reliability** ***[Level IIb]*** (Chen et al. 2002)

(continued)

Table 5.16 (continued)

System	Analysis levels	Main performance indicators
Harbour		***Container terminals:***
		Container Terminal: **Total number of containers handled or** TCoH
		Gate: **Total number of containers' movements or** TCoM
		Bulk cargo terminals:
		Bulk Terminal: **Total cargo handled** or TCaH
		Gate: **Total cargo movements** or TCaM
Health-care		**System level**
		Hospital Treatment Capacity, or HTC (Lupoi et al. 2008)

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